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FINAL REPORT

Technology Status and Planners' Guide for In-Space Servicing

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1. Abstract

NASA, commercial, and military space plans call for a collection of space-based platforms and applications that make use of in-space servicing and assembly. As these plans mature, a planners' guide to the state of the art and technology needs will provide a valuable reference toward learning from past experience and taking advantage of existing knowledge, tools, methods, and infrastructure. This report presents a summary of the history of in-space assembly, repair, and retrieval operations, with a view of near-term directions and future plans. The current state of the art and lessons learned are summarized for satellite retrieval and repair, and for telescope assembly and maintenance. The technology readiness for in-space human and robotic operations is discussed with a description of current tools, processes, and ongoing programs. A summary of the various levels of complexity of in-space assembly and servicing is presented. Guidelines are given for planning in-space servicing tasks. Key technology and transportation needs are identified, and a roadmap for future development is presented.

2. Purpose of Document

The ability of humans and remotely-operated systems to approach and access orbiting platforms in space has been shown repeatedly since the Gemini program to be valuable in improving the capability of the platforms. As shown by Skylab repairs, Hubble Space Telescope (HST) repairs, maintenance, and upgrades, and International Space Station (ISS) assembly, extravehicular activity (EVA) servicing by humans has been shown to enable pre-planned and unplanned repair and maintenance as well as upgrades. Satellite capture and return to Earth has been performed to recover and redeploy existing satellites, include Westar and Palapa.

A number of new programs are in the planning process to capitalize on the potential for in-space assembly and servicing. These programs include space-based assembly of complex telescopes that are beyond the capability of Earth-based assembly and testing prior to launch in a single vehicle. They also include National Aeronautics and Space Administration (NASA) concept plans for a human-tended Gateway infrastructure near the Earth-Moon L1 Lagrange point. Military applications are under consideration, including the ability to rendezvous and dock with existing satellites for instrument replacement and refueling. Future commercial applications may include repair and servicing of existing communications satellites, and replacement of degraded components and antennae for which the market shifts.

This document is intended to provide users and planners with a brief summary of past experience and future technology planning for satellite assembly, repair, and servicing. It summarizes the current state of the art, and is intended to provide planners – both prospective mission planners and current technology planners – with a convenient guide for the design and operations of both the servicing systems and vehicles, and the satellites to be serviced. In the following sections, the document contains a brief summary of previous history of satellite servicing, including lessons learned (Section 4), followed by a description of the various levels of assembly and servicing tasks (Section 5). A key element of any space-based operation is access to the satellite to be serviced, so Section 6 describes the features of transportation to the various orbits to be accessed, and system interfaces between the servicing system and the target satellite. Section 7 describes techniques and design guidelines for space-based assembly and servicing, and Section 8 describes the range of methods for human and robotic servicing. The document concludes with some thoughts about future directions of in-space servicing missions, technologies, and infrastructure (Section 9).

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4. Introduction and Brief History of In-Space Servicing

4.1 Introduction

In-space servicing has been a special feature of the space program since two Gemini modules performed the first rendezvous and docking procedure with astronauts. The value of extravehicular activity (EVA) in spacecraft servicing became apparent when the Skylab astronauts repaired the solar array after it failed to properly deploy. Our experience with EVA and with robotic servicing in space has matured considerably with our design and operation of the Hubble Space Telescope, and with the design, assembly, and operation of the International Space Station. In addition to these space platforms, the Space Shuttle and its support equipment has been used repeatedly to capture satellites and either repair them or return them to Earth. We are now preparing for the next phase of in-space servicing, in which platform assembly in space as well as satellite capture, repair, and maintenance will become increasingly routine. Here we summarize previous missions that utilized in-space servicing – both planned and unplanned – and describe lessons learned from these missions.

4.2 History of Satellite Servicing

An excellent summary of the history of satellite servicing is given by Leete, et al.[1] Beginning with the Gemini missions in 1965-66, extravehicular activity (EVA) and spacecraft rendezvous and docking have been an integral part of our human spaceflight missions. Table 4-1 shows a summary of the various types of in-space servicing missions that have been conducted so far.

Year	Satellite or Technology Demonstrated	Capture	Retrieval and /or Return to Earth	Service	Repair	Assembly	Mission	Comments
1965	Gemini Rendezvous	Planned					Gemini 6 / 7	First US rendezvous with another inhabited vehicle
1966	Gemini docking to Agena	Planned					Gemini 8	First US docking with another vehicle
1969	Command Module / LEM	Planned					Apollo 9	First docking with Lunar lander.
1975	Apollo/Soyuz	Planned					Apollo/ Soyuz	First international docking in space
1974	Skylab	Planned			Unplanned		Skylab 2	
1982	(SBS)-C & Telesat-E					Launch	STS-5	First deployment of satellites from reusable launch vehicle
1983	PFTA/PDRS						STS-8	First use of SRMS
1984	OAST-1					Planned	41-D	Deploy/restow Large Solar Array Technology Demonstration
1984	Solar Maximum	Planned			Planned		41-C	LDEF deployed
1984	MMU			Planned	Planned		41-B	First flight of MMU
1984	Westar/Palapa		Unplanned				51-A	Retrieved using MMU
1985	EASE-ACCESS			Planned		Planned	61-B	Assembly of Structures-Assembly Concept for Construction of Erectable Space Structures by Extravehicular activity
1985	Syncom IV (Leasat3)	Unplanned			Unplanned		51-I	Repair
1990	LDEF		Planned				STS-33	Retrieval and return to Earth
1991	Gamma-Ray Observatory					Unplanned	STS-37	Unscheduled EVA to deploy high-gain antenna

1992	Intelsat / ASEM	Unplanned		Unplanned	Unplanned		STS-49	Planned grapple fixture for retrieval failed , EVA capture by 3 crew
1993	EURECA		Planned				STS-57	European Retrievable Carrier
1993	ORFEUS-SPAS		Planned				STS-51	Orbiting Retrievable Far and Extreme Ultraviolet Spectrometer-Shuttle Pallet Satellite
1993	HST Servicing 01	Planned		Planned	Planned Unplanned		STS-61	First servicing of planned serviceable spacecraft
1993	ROTEX			Planned		Planned	STS-55	1st demo of dexterous manipulator
1995	Shuttle –Mir 01	Planned					STS-71	First docking of Shuttle to Mir
1995	Shuttle -Mir 02	Planned				Planned	STS-74	Added Docking module with 2 attached solar arrays to Mir
1996	Inflatable Antenna Experiment					Planned	STS-77	
1996	SFU		Planned				STS-72	Space Flyer Unit(SFU)
1996	Shuttle -Mir 03	Planned		Planned		Planned	STS-76	First STS EVA on Mir, added MEEP experiments
1997	Shuttle -Mir 07	Planned		Planned			STS-86	
1997	SPARTAN, AER CAM camera flight experiment	Planned	Unplanned				STS-87	SPARTAN 201-4 attitude control failed and was manually captured during EVA
1997	HST Servicing 02	Planned		Planned	Planned Unplanned		STS-82	Magnetometer covers
1997	Inspektor			Planned, failed			Progress	German free-flying Inspektor spacecraft
1998	ISS Assembly 2A	Planned			Unplanned	Planned	STS-88	First ISS assembly mission
1999	HST Servicing 03-A	Planned		Planned	Planned Unplanned		STS-103	Repaired thermal shielding
2000	ISS Assembly 4A	Planned			Unplanned	Planned	STS-97	Repaired solar array tensioning mechanism
2001	ISS Assembly 6A					Planned	STS-100	First walkoff of robotic arm to ISS. First ever robotic-to-robotic transfer in space
2002	HST Servicing 03-B	Planned		Planned	Planned		STS-109	
2002	ISS Assembly UF-2	Planned		Planned	Unplanned		STS-111	First repair of robot (SSRMS) by EVA

Table 4-1. Summary of Previous Satellite Servicing Missions

These missions can be subdivided into four classes of missions: satellite capture and retrieval; satellite servicing and repair; Hubble Space Telescope servicing; and International Space Station. All of the capture missions to date have been well-planned beforehand, although a number of retrieval missions have been accomplished with no prior design features to allow retrieval. These categories are summarized below.

4.2.1 Satellite Capture and Retrieval

Through use of the Space Shuttle and its associated EVA tools, three satellites have been retrieved and returned to Earth: Westar-IV and Palapa-B in 1984, and the Long Duration Exposure Facility (LDEF) in 1990. The LDEF spacecraft was planned from the outset for Shuttle retrieval and return, so Shuttle attachment trunnion pins and grapple fixtures were designed into the satellite for easy Shuttle attachment and manipulation using the Shuttle remote manipulator system. The Westar and Palapa retrievals were not planned for retrieval but, since they had been originally launched by the Space Shuttle, they could be readily accommodated into the payload bay for return. They did not have grapple fixtures, so the astronauts had to retrieve them by hand using the Manned Maneuvering Unit (MMU). This recovery is a good example of the flexibility and ingenuity of an astronaut crew in performing tasks in space that had not been designed into the original hardware.

Two additional satellite retrievals occurred with the capture and re-deployment of the Syncom-IV (Leasat) satellite in 1985, and the Intelsat VI in 1992. Since the Syncom-IV satellite was originally launched by the Shuttle, the redeployment was expected to be routine, but antenna problems forced creative solutions that were facilitated by human presence and the satellite was successfully redeployed. The Intelsat VI redeployment proved to be even more challenging. After two attempts by the astronauts to attach a grapple bar to the unrestrained satellite failed, an unprecedented three-person EVA was conducted. The ASEM truss structure was used to build a platform to support the foot restraints used by the astronauts to successfully capture the 4,064 kilogram satellite and bring it into the Cargo Bay for installation of a perigee kick motor.

4.2.2 Satellite Servicing and Repair

The Solar Maximum Mission (SMM) spacecraft was launched in 1980 and terminated prematurely. During the LDEF launch mission in 1984, a Shuttle crew was sent to repair the SMM spacecraft and return it to orbit. A grapple fixture was specially designed for this mission, but the flight configuration did not exactly match the design drawings and the grapple was unsuccessful. Remote manipulator system (RMS) capture also failed because of spin introduced by the failed grapple attempt. The astronauts finally repaired the Solar Max attitude control module and main electronics box, and redeployed the satellite. This was not according to the mission plan.

4.2.3 Hubble Space Telescope

After its launch in 1990, the Hubble Space Telescope (HST) has been serviced four times. The scope of servicing objectives runs from simple replacement of components that were designed for servicing; through upgrades with new components and retrofit; to repair of elements that were not designed for repair; and unplanned, improvised repair. The first Hubble servicing mission, in 1993 demonstrated the value of serviceability by installing the Corrective Optics Space Telescope Axial Replacement (COSTAR) corrective reflectors and greatly enhancing the optics in the visible spectrum. The HST was originally designed with a large number of Orbital Replacement Units (ORUs) to allow rapid equipment changeout, as well as a number of unique tools designed for servicing. Since then, many of the servicing tasks were performed on equipment that was not designed for replacement, and additional tools have been developed. Additional servicing was performed on the most recent mission (SM3B in March 2002) which revitalized an instrument designed for infrared observations with a new cryogenic cooler to replace solid nitrogen, which had sublimed years earlier. Scientific instruments are replaced on every servicing mission with either upgraded or replacement instruments. In addition to the servicing missions that were planned, and therefore built into the design and support equipment, a hallmark of Hubble operations has been the versatility of new techniques and solutions for system improvements that don't always follow the handbook.

4.2.4 International Space Station

The International Space Station (ISS) was designed from the outset for in-space assembly and servicing. According to the original plans, even the truss structure was expected to be assembled on orbit from standard rods and connecting joints. During the preliminary design phase, the trusses were baselined as a collection of major elements that are integrated on the ground with complete cabling, interfaces, and fluid lines. Only the major truss sections and the utility connections to the pressurized modules are connected in space. With each Shuttle mission, the ISS is maintained, upgraded, and/or repaired through EVA and telerobotic operations in space.

4.3 Illustrative Design Reference Missions

To bring some form to the following sections of this report, as we discuss a variety of servicing tasks with a broad range of autonomy and complexity levels in a wide range of orbital locations, we have chosen to identify three mission concepts. These are intended as examples to illustrate the following technologies and task objectives, and not as specific design recommendations, to narrow the scope of this study. The three illustrative missions are located in low Earth orbit, in geostationary orbit, and in the Earth-Moon Lagrange region. These also represent different levels of access for humans: currently accessible with the Space Shuttle; easily accessible with current launch vehicles; and future planning of space infrastructure.

4.3.1 Earth Orbital Satellite

The first reference mission, which we will refer to as LEOSAT, is to perform an unplanned repair of a satellite in a Space Shuttle-accessible orbit, i.e. altitude below about 800 km and inclination below 51 degrees. This involves approach and rendezvous with a spacecraft, attaching to the spacecraft at sites that may or may not have been designed for attachment, repair or replacement of components and/or instruments, and redeployment of the satellite.

4.3.2 Large Space Structure

The second reference mission, which we will refer to as Large Space Structure (LSS), is to assemble and maintain a structure in space with elements larger than the size of existing launch vehicle payload fairings. This mission involves in-space assembly, checkout, and deployment according to a developed plan, with or without human presence. The structure may be a large space telescope, a long-term infrastructure element such as a fuel depot or a maintenance shed, or a solar power satellite (SPS).

4.3.3 Gateway Telescope

The third reference mission, which we will refer to as a Gateway telescope, involves assembly in the region around the Earth-Moon L1 Lagrange point of a telescope designed for operation in deep-space. This mission assumes the presence of a well-developed infrastructure, with routine transportation to and from Earth and adequate communications and facilities which allow temporary human presence as appropriate.

5. Levels of Assembly and Servicing Tasks

If in-space servicing is to become routine, it may be useful to categorize the levels of servicing in terms of task complexity, autonomy, mix of humans and robots, and impact on client satellite design.

5.1 Definitions

So far, on-orbit assets are generally launched as a single unit. Initial examples of servicing of on-orbit assets have dealt with clients such as HST, Solar Max, etc., that have been launched as a single unit. Space assets whose size and complexity necessitate in-space construction of components transported to space in several launches may require in-space assembly and servicing. We are currently observing this in-space construction in ISS construction and servicing. Future platforms that will need to be assembled in space from components transported in several (perhaps many) launches may include large telescopes, fuel depots, and solar power satellites. It will be helpful to define a few terms here:

Assembly: The attachment and integration of components of a satellite or space platform to form an operational whole. Assembly in space is necessary for space platforms that are too large to launched on a single vehicle, or require in-space integration, deployment, or alignment of components for a variety of reasons.

Servicing: Repair, component replacement, upgrades, retrofit, retrofit repair, or improvised repair of a currently or previously operational space platform. Fluid transfer is also included in repair. Servicing can consist of maintenance or repair.

Client: The in-space platform or spacecraft that requires servicing or assembly. This is the telescope, depot, platform, or spacecraft that remains in space, generally at a given orbit, with an operational mission.

Servicer: The mobile spacecraft that actively approaches the client spacecraft with servicing/repair tools This spacecraft has transportation capabilities to go from a home orbit to the client and has the ability to approach the client and repair, replace, or assemble the client to be serviced.

5.2 Complexity

Servicing can be categorized in terms of task complexity, as shown in Table 5-1. The table delineates five levels of servicing complexity, which are further defined below. Examples of types of repair for the three illustrative design reference missions (LEOSat, Large Space Structure, and Gateway Telescope) are also shown in the table.

5.2.1 Replacement Form-Fit-Function: The removal and substitution of a non-functioning ORU with a functioning ORU that is identical or nearly identical, for the purpose of restoring previously existing functionality. Example: the replacement of a failed wide-field camera on a space telescope with a new one with identical capabilities. Future replacement missions may involve replacing an ORU on a LEOSAT, or replacing a solar array panel on a solar power satellite.

5.2.2 Upgrades: The removal and substitution of a functional or non-functional ORU with an ORU designed to carry out the same basic mission, but with improved capabilities. Example: the replacement of a wide-field camera on a space telescope with a new one that has improved resolution and/or increased field of view.

5.2.3 Retrofit: The placement of a new piece of equipment on a space platform for the purpose of adding additional mission capability. Example: the installation of a cryogenically-cooled infrared camera on a space telescope where there was only passively cooled or uncooled cameras before.

5.2.4 Retrofit Repair: The placement of a new piece of equipment on a space platform for the purpose of restoring lost mission capability; the new equipment may differ in form, fit, and, to some extent, function from that which it replaces. Example: placing a new antenna on a LEOSAT to replace one that is damaged, or to add new frequency capability (this category is applicable assuming that the LEOSAT is not designed to have its antenna repaired or replaced).

5.2.5 Improvised Repair: The restoration of lost function on a space platform in a manner that is devised in-situ in response to an unexpected situation using available materials, tools, procedures, interfaces, and structures. This may be necessary on a LEOSAT not designed for servicing (e.g., deploying a stuck solar array or antenna; the latter was attempted remotely on the

Galileo probe). For a Large Space Structure, improvised repair may be necessary on those portions of the structure that are not modular, or cannot be changed out without affecting other components (e.g., a damaged truss). Improvised repair includes both temporary patches (i.e., "jury-rigging"), and more permanent fixes, and thus can include cutting, forming, and welding.

LEVEL	FUNCTION	EXAMPLE DESIGN REFERENCE MISSIONS			SVCING ACCOM. REQ'TS (SEE TABLE 5.4)
		LEOSAT	LARGE SPACE STRUCTURE	GATEWAY TELESCOPE	
I	Replacement Form-Fit-Function may incorporate minor changes within ORU interface specs	Perhaps ORU changeout, if so designed.	New solar array panels or microwave transmitter array panels for SPS.	Changeout ORUs (comm modules, cameras, avionics, reaction wheels). Replace mirror segments.	4, 5
II	Upgrades significant new content, meets existing interfaces		Upgrade electronics. Add additional tanks to fuel depot for increased capacity.	Add cameras with increased sensitivity, spectral range, field of view or angular resolution, spectral resolution, etc.	4, 5
III	Retrofit totally new designs, adapted to interface to existing structures		Add tanks to fuel depot to accommodate a different type of fuel (e.g., add cryo capability to depot used for storables).	Add additional mirror segments. Add cameras with increased spectral range (e.g., cryo-cooled IR).	3, 4, 5
IV	Retrofit Repair not designed for repair, adapted to interface to existing structures, replace or workaround lost function	New solar arrays. New antenna (e.g., to replace damaged antenna, or to add new frequency capability).	Repair power bus on SPS. Route power around missing SPS panels.		1, 2, 3, 4, 5
V	Improvised Repair devised in-situ in response to unexpected situation, using available tools, materials, procedures, interfaces, structures in creative application	Deploy stuck solar array or antenna.	Repair damaged truss.	Repair damaged truss or sun shield.	1, 2, 3, 4, 5

Table 5-1. Servicing Levels

5.3 Compatible Tasks and Conditions

As larger space platforms are built, and as more is invested in on-orbit servicing, servicing is expected to become "easier" [Ref.2, p.7], and more economical, in comparison with replacing the space platform. Servicing may involve restoring lost capability, maintaining existing capability, enhancing capability, or all three. Enhancing capability may take place when a component on a satellite fails several years into its mission, after the technology of the failed component has improved. The practicality and desirability of servicing may depend, in part, on the relative size and cost of the component to be replaced or repaired. For example, a satellite with a mass of many tonnes which costs hundreds of millions of dollars may be unable to carry out its mission, due to the failure of a sensor with a mass of a few kilograms which costs just a few million dollars. Likewise, such a satellite may be functional, but obsolete, due to technological improvement affecting one component. It may be more cost-effective to pay for a new sensor, plus operation cost and amortization of the servicing system (assuming investment in on-orbit servicing [Ref. 2, p. 7]), than to launch a replacement satellite. Lower levels of servicing, as described in Table 5-1, may have a lower recurring cost of repair (for a given type of repair; i.e., replacing a communication unit) than higher levels, but possibly at a price of a high non-recurring development cost of the servicing system. Higher levels of servicing, as described in Table 5-1, may have high recurring costs for individual servicing missions, but may not have high non-recurring development costs. Time may also be a factor in the decision whether to repair or replace a satellite, because repair may take place more quickly than replacement. This is especially true for capabilities that are considered essential, such as weather satellites, military surveillance satellites, etc. Time may also be a factor in deciding whether to repair or replace a commercial satellite, due to the net present value of lost revenue during the down time.

The decision whether to repair or replace a large structure on a satellite may depend on how it is integrated into the satellite. Large structures that are assembled from smaller components may be more easily repaired than those that consist of a single unit. For example, a Hubble-class (or somewhat larger) space telescope having a single large primary mirror may not easily lend itself to replacement (let alone repair) of the mirror; it would probably pay to launch a new telescope. (However, a mission to salvage ORUs may be cost-effective, especially if it serves other purposes, such as de-orbiting the telescope, or towing it to ISS for long-duration exposure studies.) Furthermore, such a mirror may be too large in dimensions and mass to be designed as an ORU. However, for an equally large (or larger) telescope having a segmented mirror, it may pay to replace individual damaged segments, especially if they are on the periphery of the structure. The European XEUS telescope is designed to have more mirrors added, so it is likely that telescopes can be designed with replaceable mirror segments. Similarly, a solar power satellite assembled from thousands of individual solar array panels would lend itself to replacement of damaged or failed panels. It may pay to replace a considerable portion of the full array, rather than build a new satellite. As the design of large space platforms becomes more modular, repair or servicing becomes more like assembly.

5.4 Facilitating Conditions and Features

The conditions required for servicing will depend on the type of servicing to be performed. For most types of servicing, a servicing vehicle (with crew or robotic) will need to rendezvous with the satellite. The servicing vehicle will generally have to take the active role, because the client satellite may be non-functional, may be powered down (either due to malfunction, or due to safety considerations), or may not have been designed to take an active role in rendezvous (e.g., very large platforms, such as large telescopes, habitats, or solar power satellites). Vision targets may be needed on the client satellite. For ORU changeout or fluid transfer, standard interfaces will be required. This could involve standard latches, connections, and couplers; ORU bays of standard dimensions; etc. Other requirements will depend on the specifics of the satellite, its mission, and the servicing system architecture. For example, if the satellite (or a component thereof) needs power while being serviced (or for checkout), it may be necessary to transfer power from the servicing vehicle to the satellite. Communications crosslinks between the servicer and the client, or a communications link between the servicing system and the client's ground station may also be needed.

Safety of the servicing system and the satellite to be repaired is an important consideration, especially for human servicing. For the latter, the client satellite and servicing tools must not have unacceptable electrical or electromagnetic hazards (i.e., high-current connector mate/demate, high radiofrequency fields, etc), thermal extremes, mechanical hazards (e.g., sharp edges [1]), etc. Conversely human and robotic servicers must not subject the satellite to electromagnetic, thermal, mechanical, or plume/suit effluent-impingement hazards. Capture must be sufficiently soft to avoid damaging the satellite.

5.5 Levels of Autonomy and Human Involvement

A servicing architecture must optimize the mix of humans and robots. There is insufficient relevant data [Ref. 2, p. 11], so trades and tests must be done. Even with a robot-only presence, human beings will ultimately be in the loop. The degree and manner in which humans interface with robotic systems is described in Table 5-2. Level 3.2 (Unsupervised Autonomy) is probably an unachievable (and perhaps undesirable) abstraction, as even a highly-automated system will occasionally communicate with the ground - it is included in the table as a means of "bounding the problem." (The University of Maryland workshop reached a consensus that humans in the loop are required for high mission reliability of complex missions.) This table describes the manner in which humans issue commands to robots, but does not indicate the on-site mixture of humans and robots. Four categories of such mixtures are described in Table 5-3. A complete servicing architecture may consist of several elements, each of which may have a different level of autonomy. For example, an astronaut performing EVA repairs may work alongside a teleoperated robotic arm. The overall level of autonomy that a servicing system architecture is regarded to have will depend on context. For example, the designer of a client satellite may wish to describe the overall autonomy level by that of the element that interfaces most directly with the satellite. Thus, Hubble repairs could be regarded as having an autonomy level of 1.0 (Human EVA), even if the astronauts were supported by a teleoperated robotic arm. The designer of robotic systems may wish to categorize the system differently. Various human/robotic mixtures may have an appropriate level of teleoperation associated with them. For example, Category B – Human Presence (i.e., without robots) – is, by definition, autonomy level 1.0. Category C – Robotic Presence – will be associated with increasing levels of autonomy as technology develops in time. Category D – Humans and Robots – is likely to involve autonomy level 2.1, since, if humans are present on-site, remote teleoperation (with its resulting latency) may not be necessary. Furthermore, the line between teleoperation and autonomy may be indistinct as latency grows longer. For long latency periods, teleoperation becomes more like uploaded commands; i.e., level 2.2 gradually becomes more like level 3.1.1. The round-trip latency from the Earth to the Moon, or Earth-Moon libration points is on the order of 2 to 3 seconds. It may be possible (though awkward) to control a robot over such distances by issuing individual commands to move each joint; this can still be regarded as level 2.2. However, for servicing of a telescope at the Sun-Earth L2 point, the round-trip latency is 10 seconds. Repetitive tasks would likely be preprogrammed, and initiated by uplinked commands from Earth; i.e., level 3.1.1 or 3.1.2. For improvised repair, or other tasks involving unforeseeable circumstances, moving joints and actuators individually may be necessary; i.e., a temporary reversion to level 2.2. A telescope that is launched from Earth unassembled, then assembled by onboard robots as it is transported to Sun-Earth L2 may require that the level of autonomy increase as distance from Earth increases. It may be possible to devise an assembly architecture in which those tasks that require human intervention are done at the outset of the trip, or at Earth-Moon L1, with robots taking over as the telescope approaches Sun-Earth L2. If this is not feasible, it may be desirable to design the entire assembly sequence to accommodate the worst-case latency.

1.0 Human EVA
2.0 Teleoperation
    2.1 On-site Teleoperation
    2.2 Remote Teleoperation
3.0 Autonomy
    3.1 Supervised Autonomy
        3.1.1 Require ground approval before execution
        3.1.2 Allow ample time for ground override before the onboard system automatically carries out a command
        3.1.3 Run autonomously, sending commands to the ground for occasional verification
        3.1.4 Fully automate operations, with ground analysis only when a problem occurs
    3.2 Unsupervised Autonomy

Table 5-2. Levels of Autonomy

	CURRENT CAPABILITY	FUTURE CAPABILITY — NEAR TERM	FUTURE CAPABILITY — FAR TERM
A. No Presence	Commanded reconfiguration of assets, operational workaround	On-board autonomous reconfiguration of assets, operational workaround	Very long duration mission
B. Human Presence	Human EVA, Shuttle or ISS based [1.0]	Minimal-impact servicing [1.0]	Human access beyond near-Earth orbits [1.0]
C. Robotic Presence	Direct human control, Shuttle or ISS based [2.1]	Remotely-operated telerobotic servicing [2.2]	Minimal-impact servicing [3.x]
D. Human-Robotic Presence	Direct human control, Shuttle or ISS based [1.0+2.1]	Minimal-impact servicing [1.0+2.1]	Human access beyond near-Earth orbits [1.0+2.1]

Table 5-3. Categories of Human/Robot Combinations. [Relevant autonomy level in brackets.]

5.6 Required Conditions

5.6.1 Mission Planning

Mission designers may need to consider both planned and unplanned servicing. Generally, planned servicing corresponds to servicing levels I, II, and III (Table 5-1), while unplanned servicing can incorporate any of the five levels (i.e., improvised repair [level V] is generally a response to an unexpected situation; however, even the need to replace an ORU [level I] may sometimes be due to unexpected failure). It is important to note that unplanned servicing is not the same as unscheduled servicing. Unscheduled servicing is, by definition, always unplanned. However, even a scheduled maintenance visit could involve unplanned repairs.

In planning a servicing mission, appropriate human, robotic, hardware, software, material, transportation (vehicle, propellant, ground control), and supervisory resources must be allocated. The servicing level (Table 5-1) must be identified. The appropriate mix of humans and robots (Table 5-3) must then be identified. This will then lead to an appropriate level of autonomy (Table 5-2). It will also lead to appropriate considerations of safety and human/robot interaction; i.e., mutually safe emissions, electromagnetic, radiation, and mechanical environmental requirements, as well as exclusion zones. The choice of human/robot mix and level of autonomy must be made in the context of risk assessment. If a teleoperated servicing mission has a high risk (probability and consequence) of not proceeding according to plan, then this could affect the choice of on-site versus remote teleoperation; i.e., the former may allow for contingency EVA.

5.6.2 Requirements on Payloads

Most currently-existing spacecraft are not designed for servicing. A significant exception is HST, which is designed with ORUs. In addition, some of the repairs to HST have been unplanned; e.g., retrofit of COSTAR, and improvised blanket patches. The design of future spacecraft opens up a range of possible approaches for serviceability, as shown in Table 5-4. Note that most spacecraft to date have been mission-optimized, and not designed for servicing, so are regarded as Category 1 in this table. HST can be regarded being a strong 3 or weak 4, as "'Almost everything not welded to the vehicle or located inside the forward light shield is replaceable,'" [1]; however, there are notable exceptions. In addition, HST has three classes of ORUs, but only Class 1 ORUs are " 'fully "EVA-rated" ' " . Future space telescopes and other platforms may be designed so that equipment such as wire harnesses (not replaceable on HST) are replaceable, and that most or all of the ORUs do not need platform-unique tools. Such a telescope would be a strong Category 4, or perhaps 5, if designed in conjunction with the servicing system. Other future satellites could be designed to be compatible with a servicing system; e.g., the "next-generation" satellites, or NEXTSats, that may be serviced by Orbital Express. The decision as to what degree of servicing to give a spacecraft may be driven by economics. For example, a very large platform (such as a telescope) may be designed so that components that may be potential single-point system failure modes could be ORUs. Very large platforms in locations that are difficult to reach from Earth (e.g., libration point habitats), may be designed to be Category 1, 2, or 3, due to their inaccessibility to Earth-launched robotic spacecraft (such as Orbital Express), lack of economy of scale (i.e., for one-of-a-kind units), and the presence of astronauts onboard to perform EVA and IVA Level IV and V servicing (Table 5-1). On the other end of the spectrum of size, number of units, and accessibility, future communications satellites may be designed to be compatible with a servicing system such as Orbital Express (i.e., "NEXTSats,"), and may be considered Category 5 in Table 5-4.

Category		Description	Examples	Potential Servicing Levels (see Table 5.1)
1	Simple or mission-optimized spacecraft	No special servicing accommodations	Boeing 601 & 702; most satellites to date; Chandra telescope; Webb Space Telescope	IV, V
2	Generic or modular spacecraft	Some inherent system partition	Solar Maximum Mission, Landsat, UARS, Compton, Chandra Telescopes	IV, V
3	Minimally serviceable spacecraft	Some rudimentary accommodations	DRM, LEOSAT	III, IV, V
4	Designed for servicing	Architectural features incorporated in design, build, test	HST; ISS; DRM: Large Space Structure	I, II, III, IV, V
5	Integrated servicer-client system	Mutually designed for interoperability, interdependence	Orbital Express; "NNGST" [5]; DRM: Gateway Telescope	I, II, III, IV, V

Table 5-4. Servicing Accommodations Requirements on Client Spacecraft [3]. Possible future space platforms are indicated in *italics*. DRM = Design Reference Mission, as defined in Section 4.3.

5.7 Existing Equipment and Programs

Currently, the only human servicing systems are the shuttles, ISS, and their associated equipment. Human servicing has been performed on HST, ISS, Solar Max, and Mir. Several satellites (Westar/Palapa, LDEF, Syncom-IV, and Intelsat VI) have been retrieved, and in some cases, re-deployed, by Shuttle astronauts. The only ongoing human servicing programs are upcoming HST servicing missions, and ISS construction/servicing.

The only American vehicle that is currently qualified to carry astronauts into space is the Space Shuttle, so all human servicing missions for the near-term will require Shuttle use. Available equipment for human servicing, including manipulators, tools, and foot restraints, will be discussed in Section 8 below.

For HST, all five levels of servicing (Table 5-1) have been performed. For HST and ISS, the levels of autonomy that have been utilized are 1.0 (Human EVA) and 2.1 (On-site teleoperation) (see Table 5-2). Shuttle and ISS missions have included categories B, C, and D in Table 5-3, with robotic assembly and servicing being done by on-site teleoperation. "Commanded reconfiguration of assets, operational workaround" (Table 5-3, category A; current capability) has been performed several times, including attempts to deploy the stuck antenna on the Galileo probe to Jupiter, and the routing of data at a slower rate through a smaller antenna when this failed. The robotic servicing that has been done so far falls into autonomy level 2.1 (on-site teleoperation) in Table 5-2. The Shuttle robotic arm has also been used as a crane to support astronauts during EVA servicing.

Two near-term future robotic servicing programs that are underway include XSS-11 and Orbital Express. Proximity operations between two spacecraft will be demonstrated as part of the ST-6 mission, scheduled for flight with an Air Force XSS-11 spacecraft in 2004. The Orbital Express program will repeatedly demonstrate the feasibility of autonomously upgrading, refueling and reconfiguring satellites, with the spacecraft scheduled for launch in 2005. [4]

6. Access to Satellites

6.1 Introduction

To carry out a servicing mission, one must first plan the mission in advance, then transport the servicing vehicle to the client location, communicate with the ground (and possibly client spacecraft), perform the servicing, then depart. Planning the mission may involve classifying it in terms of level of autonomy and human/robotic mix, as described in Section 5. These decisions will be driven, in part, by the location of the client, because human beings are currently limited to those locations in space that are accessible by Shuttle. Level of autonomy for servicing clients beyond Shuttle-accessible orbits will also be dependent on location (e.g., on-site teleoperation currently can take place only in Shuttle-accessible orbits). Another important decision in servicing mission architecture design is the type of interface between the client and the servicing system, once the latter has been transported to the client's location.

6.2 Satellite Location

6.2.1 Near Earth Orbits

For the purpose of examining space access, near Earth orbits can be divided into those that are directly Shuttle-accessible, those that are "semi-Shuttle-accessible" (i.e., accessible through a combination of Shuttle and upper stage or OTV) and those that are not Shuttle-accessible. This will help determine whether or not human or on-site teleoperated servicing is feasible. Near-Earth orbits cover the range from low Earth orbit (LEO), middle Earth orbit (MEO), and highly eccentric Earth orbit (HEO). The dividing lines between Shuttle-accessible, semi-Shuttle-accessible, and Shuttle-inaccessible orbits are indistinct, and may be different for differently-sized Shuttle payloads.

Shuttle-accessible orbits allow direct access of the crew to the client to be serviced. Thus, both human servicing and on-site teleoperated robotic servicing are possible from the Shuttle. So far, these are the only types of servicing that have been done in space. The vehicles involved were the Shuttles themselves, or Russian piloted vehicles. Shuttle-accessible orbits have altitudes of 250 to 800 km, with inclinations from 28.5º to 57º. The inclination limitations are largely due to launch safety considerations; i.e., the locations where the solid rocket boosters and external tank are jettisoned. Furthermore, more highly-inclined orbits could be attained if the Shuttles could be launched from Vandenberg Air Force Base, but the Shuttle launch facility there is not operational. Shuttle-accessible orbits include the orbit of ISS, at 370 km and 51.6º, as well as the Hubble Space Telescope at 590 km and 28.5º. The 800-km altitude is an upper bound. The greater the deviation from 28.5º, the lower the amount of mass that the Shuttle will be able to take to orbit, and the lower the altitude that the Shuttle will be able to attain. It may therefore be desirable to consider lower inclinations for future LEO satellites. Certain LEO missions are carried out not by a single satellite, but by a fleet of satellites in several planes, usually all having the same altitude, inclination, and eccentricity. Such a fleet, or constellation, may be used when continuous coverage of most of the Earth is desired. Such constellations may provide a large market for human or on-site teleoperated servicing if they are in Shuttle-accessible orbits. For low altitude constellations, it may be feasible to lower the inclination of the satellites somewhat, while raising the altitude to compensate for lost coverage at higher latitudes. Corresponding changes in optics and sensors may also be necessary. Needless to say, Shuttle-accessible orbits can also be accessed by expendable launch vehicles, such as the Delta and Atlas families of vehicles. ELVs may prove more economical for remotely teleoperated or autonomous robotic servicing, such as Orbital Express.

"Semi-Shuttle-accessible" orbits are those LEO and MEO orbits whose altitude/inclination combinations make them inaccessible by Shuttle alone, but accessible by a servicing vehicle that is launched from the Shuttle and then transported to a higher altitude and/or different inclination by an upper stage, OTV or space tug. Clients in such orbits are directly accessible by robots only, unless a piloted vehicle is developed that can access such orbits. Such a vehicle may be either Shuttle-deployed or launched on an ELV (e.g.., a human-rated Delta-IV Heavy). Alternatively, an OTV or space tug may be used to bring such a client to ISS or to a Shuttle-accessible orbit, so that human or on-site teleoperated robotic servicing can be performed.

Shuttle-inaccessible orbits are those whose altitude/inclination combination make them infeasible to be reached from the Shuttle, even in combination with an upper stage. Typical of such orbits are polar sun-synchronous orbits. These have inclinations slightly greater than 90º (e.g., 96º or 98º), and are used by climate monitoring satellites. Due to the large delta-V, and hence, propellant requirements needed to change the inclination from that which the Shuttle is launched to, to more than 90º, it is unlikely that an upper stage or OTV will be developed to transport a servicer from the Shuttle to such a client (or to bring the client within reach of the Shuttle), even if on-orbit refueling becomes available. A similar situation holds for clients in highly elliptical orbits, such as Molniya orbits used by Russian communications satellites. Molniya orbits have an apogee of 40,000 km, a perigee of 500 km, and an inclination of 63.4º or 116.6º. The orbital period is 12 hours, but approximately 11 hours of each orbit are spent over the northern hemisphere. A servicing system will have to be dedicated to such a client, due to the difficulty of reaching such an orbit from most other orbits. However, one servicer can service clients in several Molniya planes by parking in an orbit whose semi-major axis is slightly different from the Molniya satellites, and using the resulting difference in nodal regression rate to precess from one Molniya plane to another. This may take several months, so it is best used for planned scheduled servicing. Such a technique can also be used to bring scheduled servicing to constellations of LEO/MEO satellites, such as GPS or Iridium. The servicer can orbit at the same inclination, and slightly different altitude from the constellation. The more frequent the servicing schedule, the greater the difference needed between the servicer and client altitudes to achieve the desired differential nodal regression; hence, the more propellant will be used by the servicer as it changes its altitude to rendezvous with a client. Such a technique may need to operate in conjunction with a propellant depot.

6.2.2 Geosynchronous Orbits (GSO)

Geosynchronous orbits have an altitude of 35,786 km, low inclination, and are circular, or nearly so. The disadvantage of such orbits is that they are more difficult to reach than LEO. The advantage is that once a servicing system is there, there are a great many clients (i.e., most commercial communications satellites). A GSO servicer can park in a near-GSO orbit and use the resulting slightly different orbital period to shift from one client to another, in a manner analogous to the differential nodal regression technique discussed above. This can be done with a minimum of propellant if a long travel time between clients is acceptable. The servicer can be refueled by an on-orbit depot that is stored in GSO, or in a near-GSO orbit that matches the parking orbit of the servicer. Alternatively, it may pay to launch the additional propellant no higher than low-inclination LEO, and have the servicer return to LEO for refueling. Servicing clients in GSO is likely to be robotic, as there is no currently-operational piloted vehicle that can reach that orbit. Robotic operation is likely to be autonomous, as latency issues may exist between the ground or ISS and GSO. Furthermore, autonomous robotic servicers are likely to exist in the near future (i.e., Orbital Express). Economies of scale are also likely to drive GSO servicing toward autonomous robotics. The missions of most GSO satellites are similar, and their numbers large, thereby making such satellites natural candidates for standardization (i.e., as in the Orbital Express NEXTSat concept, in which client satellites will have standard passive docking mechanisms, ORU interconnects, and fluid couplers). Indeed, many GSO communications satellites are already built from standard satellite buses, such as the Boeing 702.

6.2.3 Libration Points

The libration points have been proposed for advanced space platforms, such as observatories, bases, habitats, and manufacturing facilities. A possible location for a deep-space observatory may be the Sun-Earth L2 point (anti-Sunward on a line connecting the Earth and the Sun). The Earth-Moon L1 point, or Gateway, (between the Earth and the Moon, much nearer to the Moon) has been proposed as the location of an inhabited space station, due to the low delta-V needed to reach Sun-Earth L1, as well as the fact that the total Earth-L1-Moon delta-V is only slightly larger than the direct Earth-Moon delta-V. Thus, construction and major servicing of a deep-space observatory (i.e., a Gateway Telescope) deployed at Sun-Earth L2 can take place using astronauts at Earth-Moon L1 (Willenberg, et al). Minor servicing can be done in-situ at Sun-Earth L2 using autonomous robots (autonomy will be necessary due to latency). The telescope itself could have low-thrust propulsive capability for this, or could be carried between the two points by an OTV or space tow vehicle. The use of weak stability boundary trajectories for transfer between these points will keep propellant usage to a minimum, although transit times may be several months.

A summary of servicing clients and their locations is shown in Table 6-1.

6.3 Satellite to Servicing System Interfaces

6.3.1 Methods

The servicer and client can interact via one of three categories of physical proximity and connection: hard docking, soft capture, and standoff. Hard docking has a long heritage, going back to Gemini/Agena, and Apollo. More recently, the Shuttle has docked with Mir and ISS. Hard docking may be an appropriate choice for autonomous robotic servicing, such as Orbital Express, where a fixed geometric relationship between servicer and client is desired. Docking allows for standard fluid couplers for refueling, and, if necessary, power transfer from servicer to client. Soft capture (e.g., using a robotic arm) may be an alternative to hard docking when it is necessary to minimize loads and impact risk to the client. Once the client is captured, servicing (possibly including refueling) can proceed as in the case of hard docking. Standoff may be desirable in situations where the client is particularly fragile (e.g., space telescopes or solar power satellites constructed from gossamer structures), especially in cases of human servicing. In the latter case, standoff may help minimize the possibility of physical damage to the client by human activity, or by excessive exposure to EVA suit or Manned Maneuvering Unit emissions. The vehicles can either co-orbit, or can maintain proximity by using a robotic arm on the servicer to hold the client in place. The latter may be necessary in LEO, where the steep gravity gradient may cause the two vehicles to drift apart (unless at least one vehicle performs stationkeeping or is in a halo orbit around the other; however, either of these options could make the servicing concept of operations more complex).

Client Location	**Client Location Parameters**	**Example Clients**	**Vehicles for servicer**	**Level of autonomy of service**	**Servicer Orbit**
Shuttle-accessible near-Earth	250! altitude<1000 km, 28.5°! *i*! 57°, near circular	ISS, HST	Shuttle or ELV	Human, on-site teleoperated robotic, autonomous robotic	Same as client
Semi-Shuttle-accessible near-Earth	Up to a few 1000 km, 0°! i! 57° (perhaps somewhat higher inclination), near circular	Intelligence, Surveillance and Recon-naissance satellites	Shuttle or ELV plus OTV or upper stage	Teleoperated or autonomous robotic; human if client transported to Shuttle orbit	Same as client. May park in lower orbit.
Shuttle-inaccessible near-Earth	Polar (e.g., slightly >90°, a few 100 km); Molniya (40.000 km x 500 km, i = 63.4° or 116.6°); high altitude, high inclination MEO	EOS satellites, NOAA satellites, Iridium, GPS (20,200 km, 55°), Russian comsats (Molniya)	ELV, possibly with OTV or upper stage	Remote teleoperated or autonomous robotic	Same as client. May park in lower orbit.
Geo-synchronous orbits	35,786 km, low inclination, near circular	Commercial comsats, GOES, *solar power satellites*	ELV (or Shuttle) with OTV or upper stage	Autonomous robotic	GSO or near-GSO; may cycle to LEO
Libration points	e.g., Sun-Earth L2, 1.5M km from Earth, anti-Sunward	*Gateway telescope, habitats, manufacturing facilities*	ELV (or Shuttle) with OTV or upper stage; possible low-thrust capability on client	Autonomous robotic; possibly human at Earth-Moon L1	Servicing system for S-E L2 may be located at E-M L1.

Table 6-1. Locations of servicing client satellites. Possible future example clients in *italics*.

6.3.2 Active / Passive Vehicle Reasoning

Generally, the servicing vehicle will take on the active role in transport to the client's location, rendezvous, capture, docking, and interfacing. The reasons are as follows:

- The servicing vehicle will generally be smaller than the client, so will require less propellant;
- The client may not have access to propellant (whereas the servicer may cycle back to a propellant depot);
- The client may be non-functional;

- The business case for servicing is more likely to close if the impacts on client design and operations are minimal.

Exceptions may occur in situations where human servicing is necessary, but the client is in an orbit not accessible to piloted spacecraft. For example, a Gateway telescope may be deployed at Sun-Earth L2, with human servicing available at a habitat at Earth-Moon L1. The telescope may have low-thrust propulsive capability for transfer to the habitat. Because the habitat may have a mass that is comparable to (or even greater than) the client, the client may take a more active role in rendezvous and docking.

7. Designing for Space-Based Assembly and Servicing

There are many requirements associated with a spacecraft's design that go beyond its primary function. Along with the functional requirements are requirements related to the launch vehicle choice and the method in which the satellite is deployed on-orbit. Not only must the payloads be designed to withstand the launch environment, their size and geometry are dictated to some extent as well by the choice of launch vehicle. As the satellites become larger, and cannot be launched by a single vehicle, or the complexity is such that it cannot be deployed autonomously, it becomes necessary to assembly it in orbit. This, by no means, is a trivial requirement and can dictate much of the spacecraft and mission's design.

When designing a spacecraft, a major design choice is the primary structure. This, after all, is the framework upon which to build. However, of major concern, is the systems integration that comes with the functional requirements of an individual spacecraft that tends to be the most difficult problem for in-space construction. Integrating the systems with the structure, therefore, can be a very challenging effort.

7.1 Designing Structures for Assembly

Space structure designs can be characterized by the way they are deployed or constructed on-orbit and generally fall into four categories. The first, which is not an on-orbit assembly category, is a self-contained fully-integrated spacecraft which is deployed with a single launch vehicle. This is the most common category with numerous examples such as the Hubble Space Telescope (HST), many weather and communication satellites, and interplanetary mission spacecraft like Galileo. The second category includes satellites that are launched as pre-integrated modular components and connected on-orbit. This is a natural progression drawing upon the technologies from the first category. Examples include the Mir space station and the International Space Station (ISS). The third is to construct the satellites from their basic structural elements or piece parts, i.e. beams, struts, joints, etc. while on-orbit. The fourth is to use a deployable structure which is constructed and launched in its collapsed form and expanded on-orbit.

Most designs are likely to be a combination of the above methods and will depend on the individual spacecraft characteristics and requirements. Satellites that can be flown in a single launch vehicle usually have included deployable appendages such as antennas and solar arrays. Larger structures, such as space stations, telescopes, and solar power satellites, will most likely use a combination of pre-integrated modules, deployable primary and secondary structures, and piece part construction.

The big difference between modular pre-integrated design and in-space construction is that the design drivers for the modular design are launch and testing conditions and those for piece-part assembly are orbital conditions. By relieving the requirements of launch the in-space construction methods can take advantage of gossamer type designs as well as other choices that can improve functionality.

Method	Advantages	Disadvantages
Single Element	Little or no on-orbit assembly required. Little or no EVA required.	Size and mass limited by launch vehicle.
Pre-Integrated Modules	Only limited on-orbit assembly required. Low risk – utilizes well demonstrated technologies.	Massive structure designed for launch loads. Can be difficult to modify and repair. Limited by launch vehicle capabilities.
Piece Part	Efficient in-space design. Easiest to maintain and modify. High packaging efficiency.	EVA/EVR intensive. Difficult to integrate systems.
Deployable	Low EVA time required. Fast construction of large structures. High packaging efficiency.	Systems integration necessary. Risk present in binding.

Table 7-1. Construction Methods

7.1.1 Construction From Basic Structural Elements

Assembly from basic structural elements is the most versatile method to construct structures in space. It allows for the greatest amount of freedom in design, can be used for temporary as well as permanent structures, and lends itself to modification and repair. These features, however, come at a cost: this leaves most of the activity to be done on-orbit and consequently is the most time-consuming. This approach, when considering EVA assembly, is suitable for small-to-medium-sized structures (structures perhaps up to 50 m as the longest dimension). Until EVA becomes more routine and therefore lower cost, it would be prohibitive to construct a large space structure, such as a solar power satellite, in this manner. However, robotic assembly techniques may make this approach very attractive and the method of choice in the future. As of the writing of this paper, however, robotic construction techniques have not been demonstrated on-orbit.

Central to this construction method from basic structural elements is the technique of joining the various structural members together. The most popular method for space structures in general, is joining components with threaded fasteners. To use this method, the bolts generally have to be integrated with the structural elements such that they are captured and presented to the crewmember or robot for use. The International Space Station (ISS) uses bolted connections extensively. Bolts, however, are not without problems and limitations. It is difficult to predict bolt pre-load tension based on torque values. The problem initially exists with the difficulty in determining the proper coefficient of friction at the time of bolt tightening. This results because exposure to the space environment causes the surfaces to change their friction characteristics. Also, to design the joint properly, the thermal characteristics of the structure must be taken into account. This further limits the range of torque that is required to be applied to the bolt. However, bolted connections still remain as the easiest method to implement and with proper design can be very effective.

A very promising method for attachment of truss elements using EVA without any tools was used in the early design phases of the Space Station Freedom. It simply used an over-the-center mechanism, actuated by turning a collar, at the ends of the truss members to connect them to ball joints. However, this method is limited by the size and strength of a crewmember's gloved hand. This method was used very effectively to create a makeshift platform out of a truss flight experiment to rescue a satellite on the STS-49 Shuttle mission. Without this platform to work from, the mission may have failed. This method may have important applications for in-space construction.

On-orbit welding has already been suggested for assembly, but has not yet been extensively tested in the American space program. This method, however, may prove very useful for improvised repair and fastening, as well as a primary joining method.

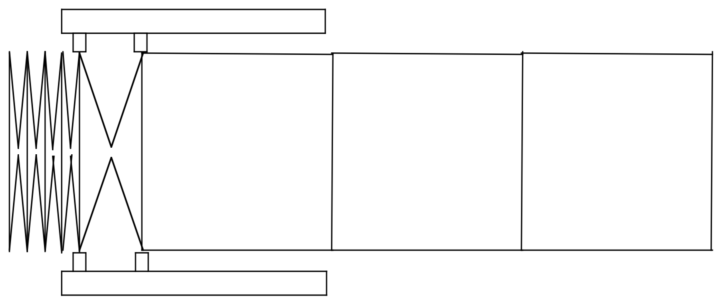
Method	Advantages	Disadvantages	Example	Comments
Bolts	Ease of application. Reversible.	Problems at cryogenic temperatures. Difficult to determine pre-load. Loosening may occur.	EVA Bolts	Most common attachment method.
Welding	Very effective for joining metals. Low mass. High stiffness.	Difficult to reverse. Not useful for composites. High energy requirements. Requires skilled technician.		Not demonstrated on-orbit.
Shape Memory Alloy	Ease of application. High strength. Mass efficient. Simple design with few moving parts.	Difficult to reverse. Expensive.	Spacecraft release mechanisms. Hydraulic fluid line coupling for F-14 & A-10.	Much research has been done with this material. Has potential for many applications.
Hand Actuated Over-Center Mechanism	Ease of application. Does not require tools.	Limited strength.	Langley joint.	Successfully demonstrated on orbit. (STS-49)
Rivet	Simplicity.	Difficult to reverse. May generate orbital debris.		Not demonstrated on-orbit.
Adhesive	Ease of application. Low mass.	Difficult to reverse. May deteriorate in space environment. Outgasses.	Labels and placards.	
Lashing	Quick and easy to apply.	Difficult to secure firmly. May damage sensitive cables.	Tethers and wire ties.	Wire ties have been very popular on ISS.
Crimping	Simplicity.	Difficult to reverse.	Huck-Bolts	Various crimping methods available.

Table 7-2. Connection Methods

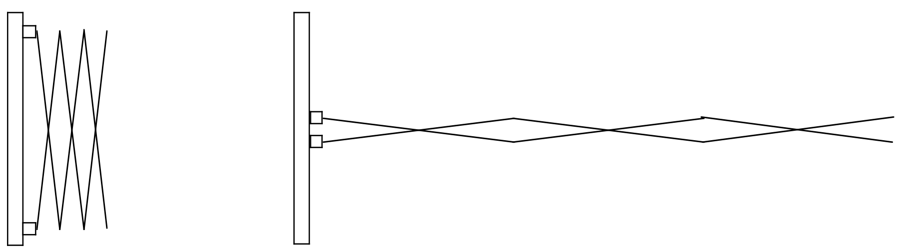
7.1.2 Assembly Using Deployable Structures

Deployable structures are very useful for minimizing payload volume and making more efficient use of on-orbit assembly time. When considering on-orbit assembly of large space structures, material handling and logistics issues can be solved by using deployable structures.

Fundamentally, there are two types of deployable structures: non-synchronous and synchronous. This characteristic describes the way in which the structure deploys. A non-synchronous structure can deploy incrementally one section at a time, and a synchronous structure is constrained to deploy in a single, continuous process. A simple example of a non-synchronous structure are the legs on a card table, while an example of synchronous structure is an umbrella. Non-synchronous deployable structures are usually simpler in design but require a separate deployment mechanism. Synchronous deployable structures, on the other hand, are usually more complex but offer a more stable and controllable structure throughout their deployment phase. The synchronous design can also have an integrated deployment system allowing for a self-deploying capability.



Non-Synchronous Deployable Structure



Synchronous Deployable Structure

Figure 7-1. Deployable Structure Types

The advantage of non-synchronous structures is that they can be "grown" from a platform one section at a time. They are well-suited for structures that deploy in one dimension, such as beams or masts. It does, however, require a sometimes elaborate and specialized deployment device, which can, on the upside, also be designed to retract the structure as well. If the structure were to be separated from its deployment mechanism, it may become unstable and difficult to control. Examples include the solar arrays on the ISS.

Synchronous deployable structures, along with being well-controllable, have the advantage of a high packaging efficiency. The structural members typically interact via linkages, which are often primary structural members themselves. Figure 7-2 shows an example of a double-folding square truss design. The deployment device need not be as elaborate as with the non-synchronous structure and can be integrated in the structure as well. Disadvantages of this design are: (1)if one of the joints were to bind it would prevent the entire structure from deploying; and (2)it is difficult to determine exactly where the binding occurs.

Typically, deployable structures are chosen for their packaging efficiency and their autonomous deployment characteristics. However, there are other advantages that can be capitalized upon. In the collapsed form, along with their overall size, their moment of inertia is far less than when deployed. This is a distinct advantage when maneuvering these structures around the worksite. In addition, deployable structures can be combined together in their undeployed form prior to deployment. Some of the logistical and mass handling issues may also be alleviated by assembling structures in their undeployed form from piece parts on orbit.

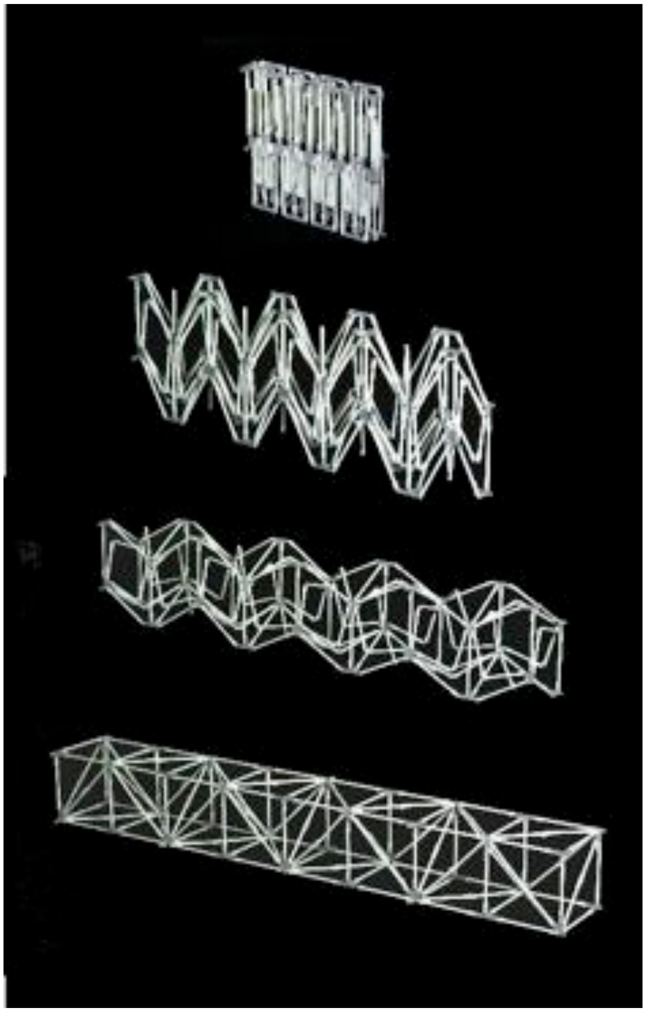


Figure 7-2. Synchronous Double-Folding Square Truss Design Concept

7.1.3 Structural Quality

Structures must not only support the loads which are applied to them but must also meet stiffness requirements and other specific needs of the mission. These can vary from basic frequency requirements needed for controllability to very stringent dynamic requirements for scientific instruments. Large structures and structures with deployable components can have difficulty meeting some of these requirements due to the construction techniques that are used.

Deployable structures face design and manufacturing challenges due to the inherent nature of the pinned joints typically used. Because the pins must freely rotate during deployment they generally have clearance fits resulting in a non-linearity in the structure. This can be important when slewing a telescope and keeping it pointed at an object of interest.

The non-linearity can be reduced by tightening manufacturing tolerances, but not eliminated unless the pinned joint is designed with an interference fit. This can be accomplished by using a ball or roller bearing design, provided the loads are not too high. This, of course, increases the cost and mass considerably. There are also some experimental designs that use shape memory metals or other methods to cause an interference fit after deployment.

7.2 Utilities/Systems Integration

Most concepts for in-space construction of large space structures focus on the structure itself. However, a major part of the construction project is the systems integration; i.e. the components that make the project function and create the operating environment. These systems can be quite varied, depending on the mission requirements but typically require power, communications, attitude control and thermal control systems. To integrate these systems on-orbit is a very challenging and time consuming task. In fact, so much EVA time was required to do this on the Space Station Freedom design that the whole project was redesigned in favor of a pre-integrated modular approach.

The large components of many systems usually include equipment mounted in boxes such as computers sensors, pumps etc. or sensing and transmitting devices such as antenna. These components are usually designed for removal and replacements, and come under the category of an ORU. They are typically translated by robot manipulator arms that interface via grapple fixtures, placed into position, secured with a fastening mechanism, and hooked up to utilities. The securing mechanisms are usually straightforward and include a soft docking feature to allow alignment and enough stability to secure the ORU permanently. Once secured, the communication and utilities are connected. This is done by electrical and fluid connectors. The design of these connectors has proven to be a challenging task. Although the International Space Station has just begun its construction, it has experienced both electrical and fluid connector problems. Evolution of the current designs needs to occur or new approaches need to be implemented.

The network of electrical and fluid utility lines is a major part of the system integration problem. Where possible, the utility line should be integrated with the structural members themselves; however, this not always possible especially when the piece part construction method is used. In this case the utility lines must be strung after the framework has been built. This has been a very challenging task, one of which the ISS designers opted away from in favor of a pre-integrated approach. However, this may not always be the best choice to make.

In order to have an efficient design the entire project, which includes the structure and all the systems, must be designed in a systematic approach that takes into account all the requirements. For example, if the structure is designed taking into consideration the EVA and extravehicular robotics (EVR) interface requirements from the outset, the design will be more efficient than if the structure were first designed and then the interfaces added. This is not the only consideration - functional requirements must be addressed concurrently as well. The special requirements of a telescope will likely have a significant effect on the overall design. These statements should be obvious. However, time and time again, expedience and conflicting agendas have caused many problems in this area. Therefore, up-front planning that can address as many of these requirements as possible is critical to the success of telescope assembly by EVA/EVR.

7.3 Assembly Platforms - ISS, Shuttle

Unless the deployment of a satellite is autonomous and self-contained, a work platform is required for assembly. Currently, the two assembly platforms that support EVA assembly are the Space Shuttle and the International Space Station. The Space Shuttle has been used as a platform for many types of experiments, as a deployment and repair platform for the Hubble telescope, and as the starting point for the International Space Station. The Space Station, however, has now become a building platform itself as its own construction continues, and can serve as a platform for other projects as well.

The Shuttle is a very versatile spacecraft and is an excellent platform for many projects. It does have, however, the disadvantage that it has a limited time that it can be in orbit. Therefore, any semi-constructed satellites must contain docking capabilities and be able to sustain themselves between flights. The Space Station has a distinct advantage of being in continuous flight and can take advantage of much longer assembly times.

A platform must not only provide a base from which to work by providing robotic and EVA support, but is must also provide the logistical support for the construction. Of primary concern, especially with large structures, is the material handling. Having a robot or EVA personnel constructing a structure requires that a steady stream of building materials must also be provided at the worksite. To provide this type of logistical support and provide a way of handling the workpiece, a device that can translate along the structure is required.

7.4 Design for Servicing and Repair

Most of the EVA and EVR compatibility consideration will be discussed in detail in the next section, but there are four important areas that are better pointed out while discussing structural design. The first is EVA and robotic accessibility: EVA accessibility requires a pathway to a particular worksite and enough area to work in. For the Space Station, the translation corridors are required to be 1.09 m in diameter and the work volumes are 1.22 m in diameter. For a square truss, this can limit the size of the bays. Also required is an escape path that does not require the crewmember to turn around in a corridor.

Another important consideration is sharp edges, pinch points, and touch temperatures. The EVA suit is vulnerable to sharp edges, especially at the fingertips of the glove. Therefore, any part of the structure that comes in contact with a crewmember must have smooth edges. Exposed fastener threads seem to be a common non-compliance. Pinch points are places where a crewmember's gloved hand may be pinched or jammed between two pieces of equipment. The pinch point need not have moving parts to be a problem: a sharp enough closing angle between two structural components may also present problems. The last concern related to the suit is touch temperature. In order for the crewmember to grasp a hardware component, it must be within a certain temperature range.

Handrails are required to aid in crew mobility and stabilization. Integrating the handrails with the structure is a very desirable characteristic: experiences on the ISS have shown you can’t have enough handholds.

Any structural attachment scheme must be compatible with available tools. The requirements associated with bolted connections are (1) captured fasteners; (2)7/16-inch head size; and (3)accessible by drivers and extensions.

7.5 Reference Examples - Gateway and Solar Power Satellites

To illustrate some of the points made earlier and provide some examples of how space structures can be built, we will look at two of the reference projects: the space telescope and the solar power satellite. The single orbit satellite is not affected by this discussion but will be included when considering serviceability. The space station is used for the platform for the construction of the telescope.

The telescope is a full aperture design with a collecting surface area equivalent to a 10 meter aperture similar to the project that has been studied by NASA’s JPL Team-X group. The first step is to determine the optical geometry and design the structure that will maintain it. For this project we will assume the existence of a thin film mirror design although it is not important to this discussion as a segmented mirror can also be used. Figure 7-3 shows the overall design we will use.

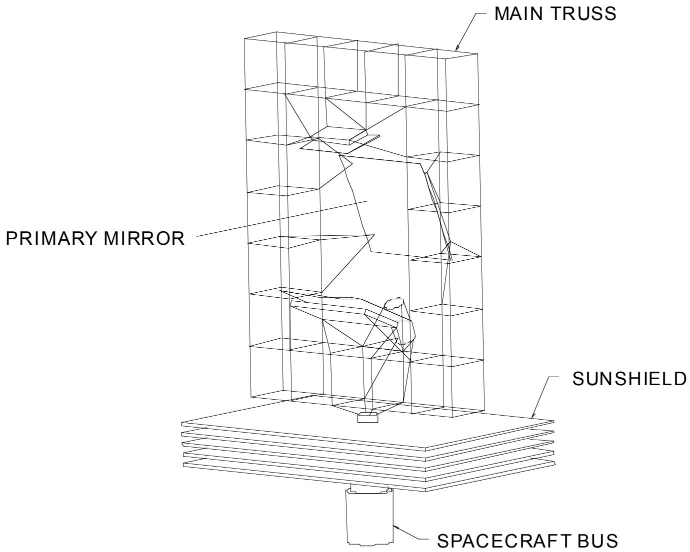


Figure 7-3. Full Aperture Infrared Telescope Concept

The main truss design was chosen for the following reasons. It is a regular truss design that can easily be constructed from piece parts or be made deployable if desired. If a deployable design is chosen, a synchronous design may be selected with an integrated deployment system. In addition, when a truss is made from parts that can be interchanged there is an advantage of reparability and changeability. It is also a design that is very stiff, provided that all the loading occurs at the joints. Whether the truss is made from piece parts or is deployable, each member should be designed such that it can be disconnected from the main truss and replaced.

The first step is to assemble the main truss structure, then install the mirrors and supporting systems. For the purpose of this illustration we will use the International Space Station as the platform with which to build the telescope but, before we begin, we must have an additional fixture to assist in the construction based of the station. This fixture is shown in Figure 7-4. It will allow for relative mobility and handling of the telescope to make use of the Space Station Remote Manipulator System (SSRMS) during construction.

To reduce payload volume and assembly time, a synchronous deployable truss is selected. Removing the truss from the orbiter and attaching it to the handling fixture can be done easily as the size and mass properties are easily handled by the SSRMS. The deployment of the truss is accomplished with an integrated deployment system and is shown in various times during its continuous deployment. Next, the modular components are added. The mirrors are installed and remain in a undeployed or otherwise protected state until such time as contamination issues are minimized. To attach these components requires a piece part assembly method in which the framework connecting the components to the main truss is installed. The other components are installed in a similar manner. Along with installing the modular components is the utilities that connect them. Ideally the utilities are integrated with the main truss structure and deploy with it, however, if this is not the case, the utility line must be strung as a separate task. Once the telescope is assembled and the spacecraft bus is attached it is released to begin its trip to the earth-moon L1 libration point.

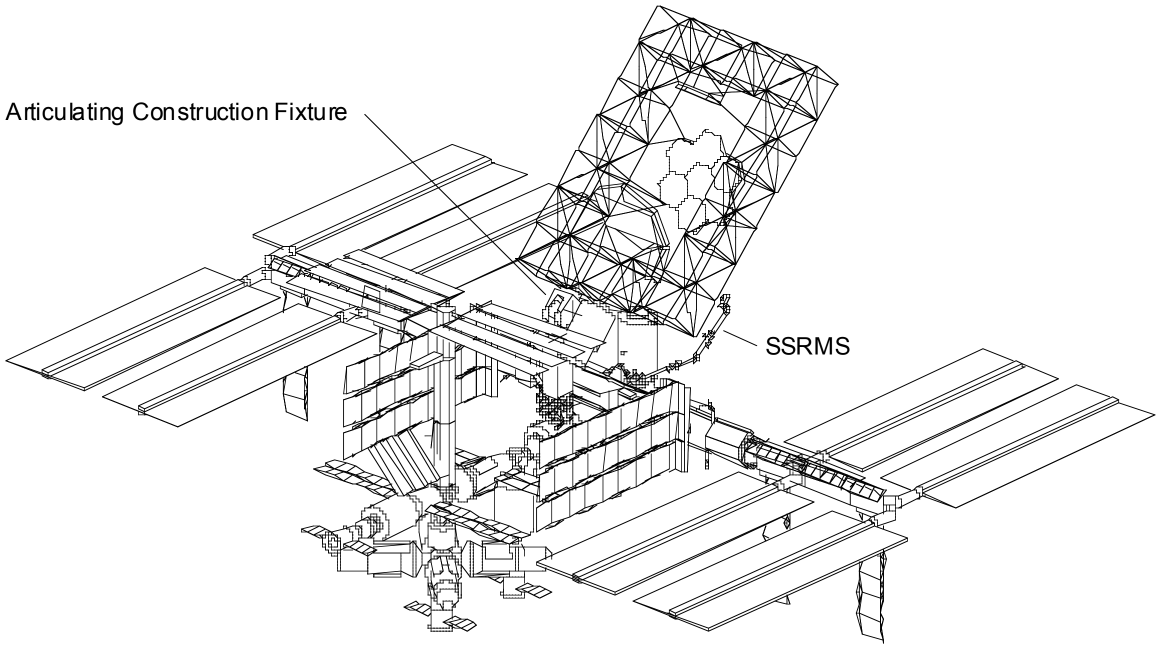


Figure 7-4. Telescope Assembly Using ISS as a Construction Platform

For the solar power satellite, we will again employ the use of a deployable structure. However, in this case the deployable structure is more important because of the size of the project, and again the use of piece part construction will be necessary to connect the deployable components. Integrating the solar panels and utility cables is especially important in this project

The platform for this project is likely to be initially the Shuttle but will quickly serve as its own platform. Crawlers are used for docking with the Shuttle, transporting materials to the worksite, and assembly assistance. One question to be addressed is when the deployment will occur. Because handling of a undeployed structure is much easier due to the smaller moment of inertia this will be the state in which it is transported. However, multiple undeployed structures could be attached together prior to the deployment of the whole.

The important point to be make is that, for the purpose of handling, the structure may best be built in a collapsed form even if it is constructed from piece parts. Much of this, however, requires some deployable structures technologies that have not yet been proven.

8. Human/Robotic Servicing Methods

In this section we will look at the how we are currently using the methods and technologies developed since Apollo to present to assemble and service International Space Station (ISS), and how these techniques apply to future satellite servicing.

8.1 Introduction

The use of humans to perform in-flight servicing of space hardware had its initiation with the repair of the Skylab in 1973. Skylab was not designed for serviceability and lacked even the most rudimentary EVA aids such as handrails for translation. In spite of this the Skylab repairs demonstrated the adaptability of EVA to perform even in adverse conditions. Telerobotic operations were introduced with the Shuttle Remote Manipulator System to deploy satellites in 1983. The ISS Space Station Remote Manipulator System was used to restow the Spacelab pallet it was launched on with the first robotic arm handoff on STS 100.

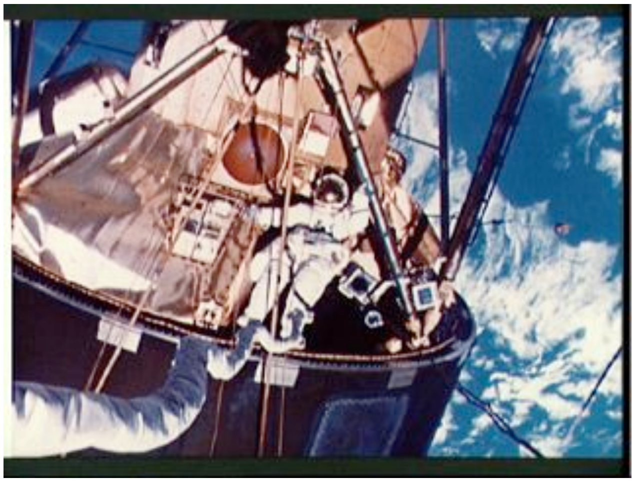


Figure 8-1. Skylab EVA Repair

Figure 8-2. Hubble 3A Servicing Mission

The Shuttle EVA flight experiments, satellite servicing missions, and the continuing Hubble Space Telescope (HST) servicing and repair missions developed the methods and tools that paved the way towards the EVA assembly and servicing of the International Space Station (ISS). ISS provides a setting to establish new standards for extravehicular activity (EVA), extravehicular robotics (EVR) and combined EVA /EVR operations.

The traditional methods used in the Shuttle program of designing the hardware and performing the neutral buoyancy testing to determine and design and build the man-machine interfaces would not be sufficient due to the sheer number of tasks being done on ISS and the size of the integrated assembly. Training for the complex assembly and maintenance tasks are still done in a neutral buoyancy tank, there are tasks the increment crews will have to perform in orbit for which they were not trained. For these reasons new analysis and training methods are being developed.

In the design and development of the ISS, new techniques and processes had to be developed to make the vehicle compatible for EVA and EVR operations. Since ISS hardware has been developed using three-dimensional solid models, this opened the door to developing a human engineering analysis method or EVA worksite analysis.

Worksite Analysis allows simulation of the crew tasks and operations to be reviewed early in the design phase, before even mockup hardware would be built. This reduces the impacts to the hardware design in incorporating the necessary design features to make it EVA/EVR-compatible. The analysis determines crew translation paths, stability aids, restraint locations, visual and hand access, tool clearances and stackups. The analysis process triggers the first cut in the operational scenarios and timelines. These are eventually turned into the EVA/EVR timelines for the mission and the logistical procedures used for on-orbit assembly, servicing and repairs. The EVA procedures resulting from the analysis is also used in the crew training process.

Another product of worksite analysis is the determination of EVA and EVR crew and robot translational corridors. By analyzing for these corridors during the design process a determination of where translational aids or interfaces can be mapped out on the vehicle. This can then show if the ORUs are accessible to the servicing agent and if there is equipment within these corridors that may restrict translation. Equipment sensitive to EVA or EVR impact loads or contamination can be identified.

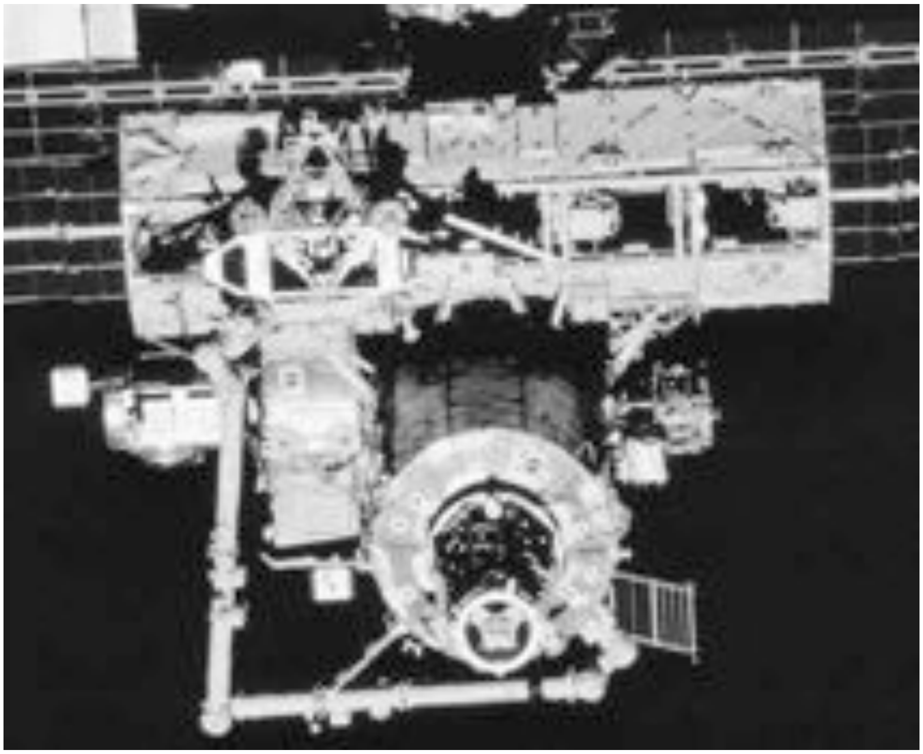


Figure 8-3. ISS MBS & SSRMS on Face One of S0 Truss

Figure 8-4 is a snapshot of EVA/EVR worksite analysis and shows how the many EVA/EVR assembly and service equipment must be integrated to work together. Not all servicing scenarios will require this level of equipment but servicer and client spacecraft should address these parameters:

Access to the location where the service will be performed
Ability to deliver equipment and consumables
Temporary stowage of new or failed equipment
Compatible tools
Translation around client to servicing worksites
Software supplementation during systems shutdown
Access to equipment being replaced or repaired
Access to and serviceable attach, electrical and fluid connections

8.2 Human Servicing

Human involvement in the role of satellite servicing really came into being with the Shuttle program. The Shuttle was the first vehicle designed for satellite deployment, retrieval and servicing while providing a habitable environment and making human access to space routine. Human servicing provides ability to assess unpredicted problems quickly. There are repeated demonstrations of this adaptability in the spacecraft servicing and space station assembly experiences. More recently the HST and ISS experiences have shown how human servicing has played an important role in performing unplanned repairs during a mission..

When adequate materials, tools and time are available, human servicing has made assessing problems, developing solutions and effecting repairs possible within a mission timeline. The ability to develop these solutions using imaginative and adaptive thinking is why human servicing capability should be considered in the development of mission architecture. If human presence will be available during assembly or servicing of satellites the complexity of the design can be reduced to take advantage of the human ability to actuate, assemble, deploy, repair and jury rig structures and mechanisms. Human capabilities for the near and mid term future can reduce the risk of unrecoverable failure while robotic technology is still maturing.

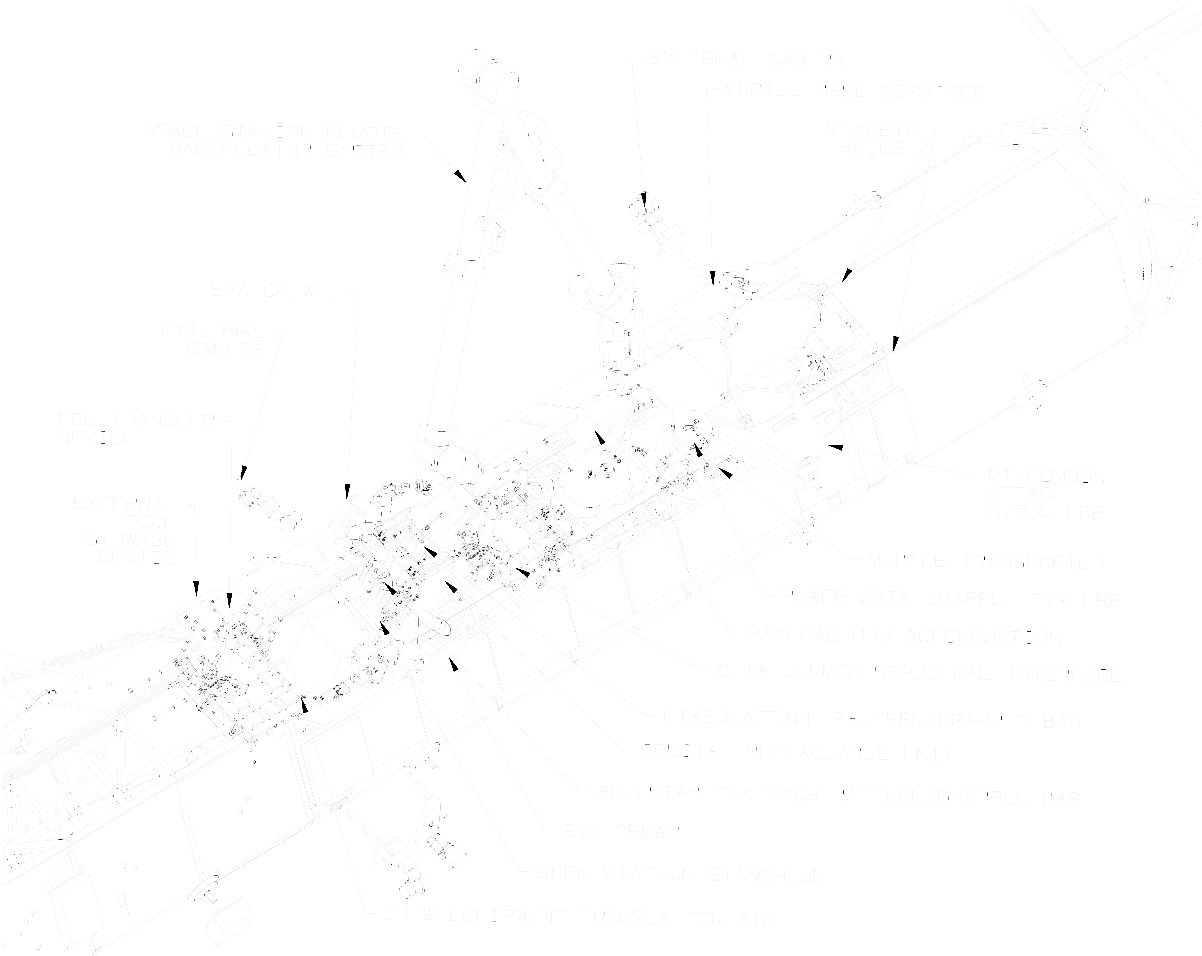


Figure 8-4. EVA\EVR Worksite Analysis[7]

8.3 Tools

The infrastructure required to do in-space servicing will require the ability to use common launch platforms and space logistics carriers. The ISS program is currently developing these means in order to sustain the ISS capabilities. Common flight support equipment, tools and procedures can reduce development and recurring costs for individual programs. Simple EVA interfaces commonly used on serviceable vehicles will reduce training and procedure development costs. These savings will flow through the entire servicing process thereby reducing costs to individual programs.

The Portable Work Platform (PWP), radiator grapple bar, ORU Transfer Device (ORUTD), Flight Releasable Attach Mechanisms, passive and active (AFRAM and PFRAM) are some of the tools developed for the servicing of ISS. The PWP consists of an articulating portable foot restraint (APFR), a workstation tool stanchion and a temporary equipment translation aid (TERA) that attaches to the end of the SSRMS. This allows for translation of large ORUs, the tools, and astronaut from the stowage site to the worksite in one trip. This methodology has many applications for future satellite servicing.

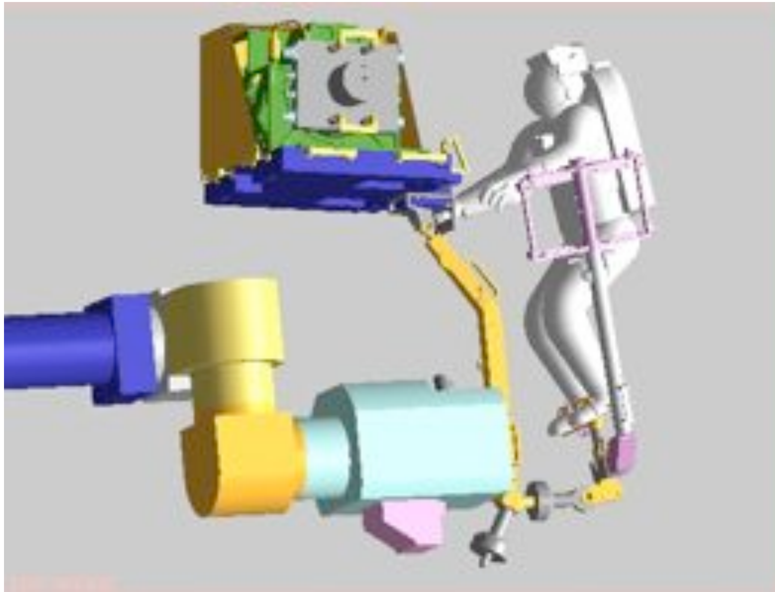


Figure 8-5. PWP with ORU on AFRAM Mounted on TERA

There are many EVA hand tools that would be found in any mechanics tool inventory that have been adapted for use in space. The primary changes made are to provide tethering points and to be operable by an EVA-gloved hand.

Figure 8-6. EVA Vice Grip – All Purpose Servicing & Repair Tool

Some of the unique tools developed for EVA are the Microconical Scoop, Micro Scoop, Torque Multiplier, and Pistol Grip Tool (PGT). The Micro tools interface with the micro conical and micro square fittings. These fittings provide a positive locking attach feature and can be combined with an EVA bolt to allow removing or installing equipment. The Special Purpose Dexterous Manipulator (SPDM) can also use these fittings to robotically change out EVR compatible ORUs.

The ISS Crew and Equipment Translation Assembly (CETA), is a human powered mobile work platform and translation aid. A rail system over 100 meters long stretches along the forward face of ISS and provides a translation path for the mobile transporter (MT) and the CETA. The CETA has five articulating Worksite Interfaces (WIF) that can be positioned to provide APFR access to the ISS truss faces 6, 1 & 2 along this rail system. Many of the ISS ORUs are positioned along these faces providing ready access from the CETA. The CETA also has an External Tools And Stowage Device (ETSD) or toolbox containing many of the small hand tools and PGT used by the EVA crew.

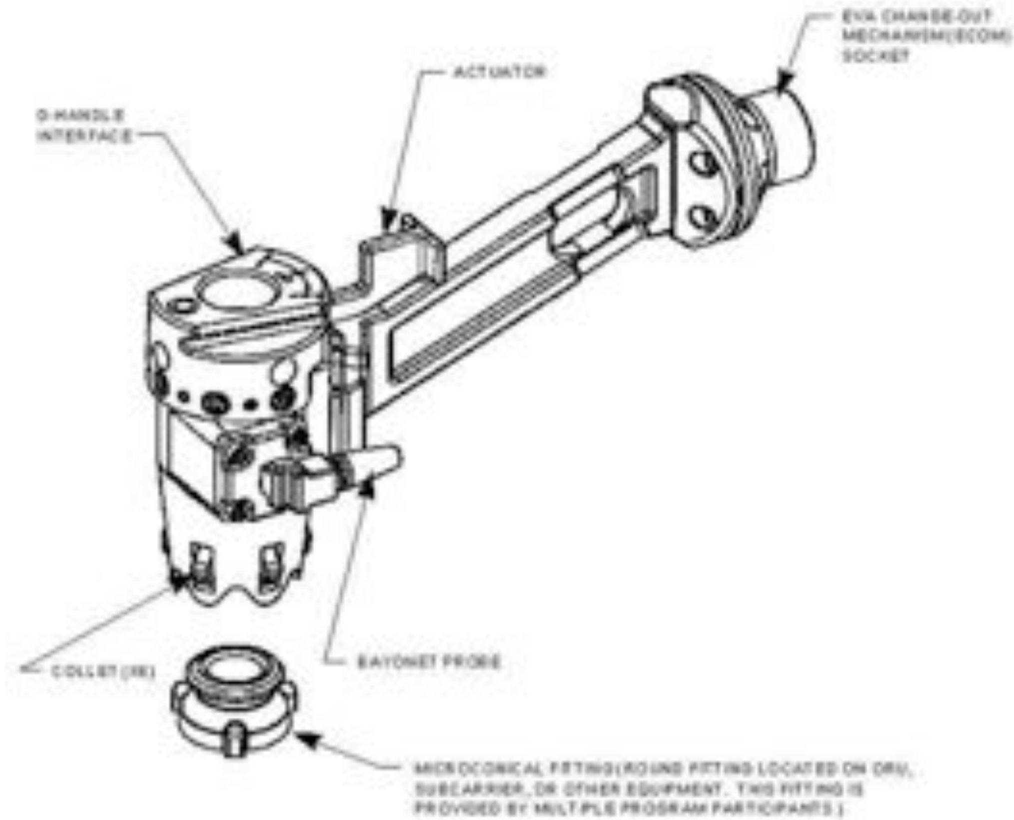


Figure 8-7. Microconical Tool and Microconical Fitting

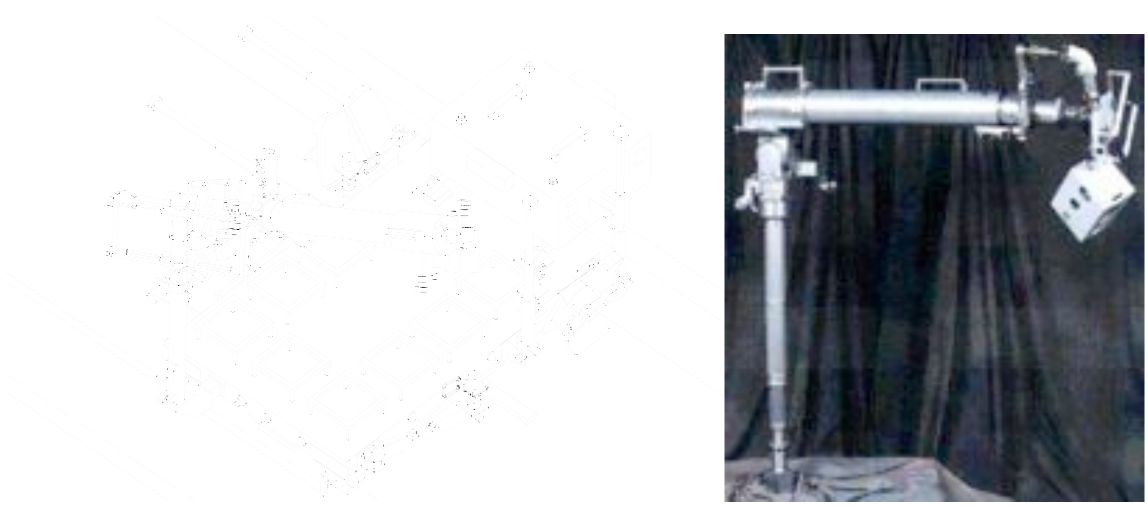


Figure 8-8. ISS Crew and Equipment Translation Assembly (CETA) & ORUTD

The CETA also provides a mobile base for the OTD or manual crane used by the crew to translate and temporarily stow ORUs being removed or replaced. The OTD has a telescoping boom that is capable of reaching from 1.3 to 4.1 meters from the CETA while moving objects up to 30 cubic meters and up to 364 kilograms. The CETA-OTD system is best suited to very large space structures such as ISS, solar power satellites, and space resort hotels, where servicing would be done on frequent intervals. A robotic variation of this system could also be developed for these giant satellites.

The Body Restraint Tether (BRT), Articulating Portable Foot Restraint (APFR), ground and On-Orbit installed handrails and Worksite Interfaces (WIF), WIF Extender, Tethers and are some of the EVA translational and restraint equipment currently used to assemble and service ISS. The Micro-conical, Micro square, PDGF, FRGF, H fixture, handrails, WIFs, ECOM (EVA Change Out Mechanism) are structural quick-connect/disconnect apparatus.

The BRT is a recent EVA device that provides a much more adaptable and portable crew restraint. Using an APFR requires the crew to translate with the 23-kg APFR to the worksite, and then setup , ingress and egress and return the APFR. The worksite also must have a WIF located within the operational reach envelope of the APFR. The BRT by interfacing with the dogbone cross-section handrails reduces the need for the use of the APFR and the required WIF for many of the EVA tasks on ISS. Integrated with the EMU, a crewmember can choose to use the BRT to accomplish many of the tasks that could not be done free-floating and do not require the full restraint provided by the APFR.

Translational tools used with the large EVR arms to aid in moving large objects include fixed grapple bars, adjustable grapple bars, radiator grapple bars that are temporarily attached to the ORUs. Providing interfaces for tools of this type on future spacecraft will allow for satellite servicing and make take advantage of these tools and procedures to use them.

8.4 Suit Characteristics and Astronaut Capabilities

"The spacesuit worn by shuttle crewmembers is called the extravehicular mobility unit or EMU. It is pressurized to 30 kPa. The EMU and Orlan are suits for an EVA based from ISS. These suits can be exposed to temperatures as high as 120 degrees Celsius or as cold as -150 degrees Celsius. The EMU is modular in design and consists of an upper torso, lower torso, arms, gloves, and helmet. A liquid cooling and ventilation garment is worn under the spacesuit and has water-cooling tubes running through it to control the astronaut's temperature to a comfortable level. A communications assembly is worn underneath the helmet, providing two-way communications with both mission control in Houston and the astronaut crew inside the shuttle. A biomedical instrumentation system is worn underneath the cooling garment to provide basic biomedical information on the spacewalker to the flight surgeons in Mission Control. The maximum total mass of the largest size spacesuit assembly, including the associated subsystems, is 49 kilograms. "[8]

Current operational limits of EMU are 340 kilograms. Nominal EVAs are 6 hours in length although 8 hour long EVAs have been done. Extensive overhead in crew preparations, prebreathing, suit doffing and donning, suit preparations and servicing, as well as crew exertion limit the number of EVAs that are currently conducted per STS missions.

Improved suit technology could reduce EVA overhead and allow longer EVAs. As operational procedures are continue to be developed and mature the number of IVA/Ground personnel required to support each EVA crewmember and each EVR telerobotic operation could be reduced resulting a reduction in cost per operation.

University of Maryland Space Systems Laboratory is developing a unique, “Power Glove” which facilitates gloved motion of the major hand joint, the metacarpophalangeal. The new actuator provides torque to counterbalance those induced by the pressurized glove, enabling near "nude-body" hand mobility with reduced arm fatigue.[9]

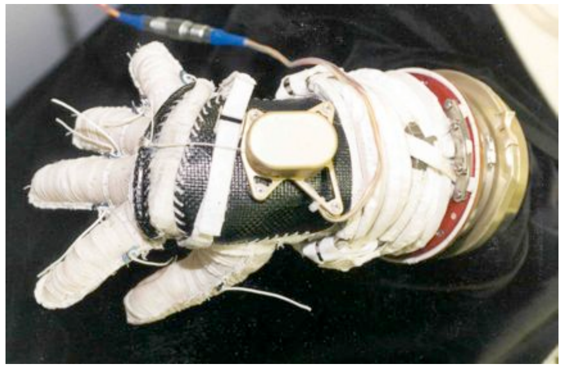


Figure 8-9. Power Glove for EMU[9]

Improved flexibility, dexterity, radiation protection and lower out-gassing are suit improvements that may allow for human servicing of spacecraft at GEO and gateway locations.

Air to ground audio communications are channeled through STS and ISS and can be continuous. Video communications is limited by satellite and ground station coverage. The Helmet mounted cam allows IVA and ground support to see what the EVA crew sees. This provides a quick way to relay problems to the ground for problem assessment and new procedures to be created.

A Suit heads up display plugged into a database will provide real time access to database that the crew can access for timelines, procedures and imagery to review while conducting a current task. Video from other EVA crew head cams or EVA inspection camera can provide flexibility in dealing with unexpected events during an EVA. Revisions to timelines and procedures are currently e-mailed to crew prior to EVA for comments and feedback to make required adjustments.

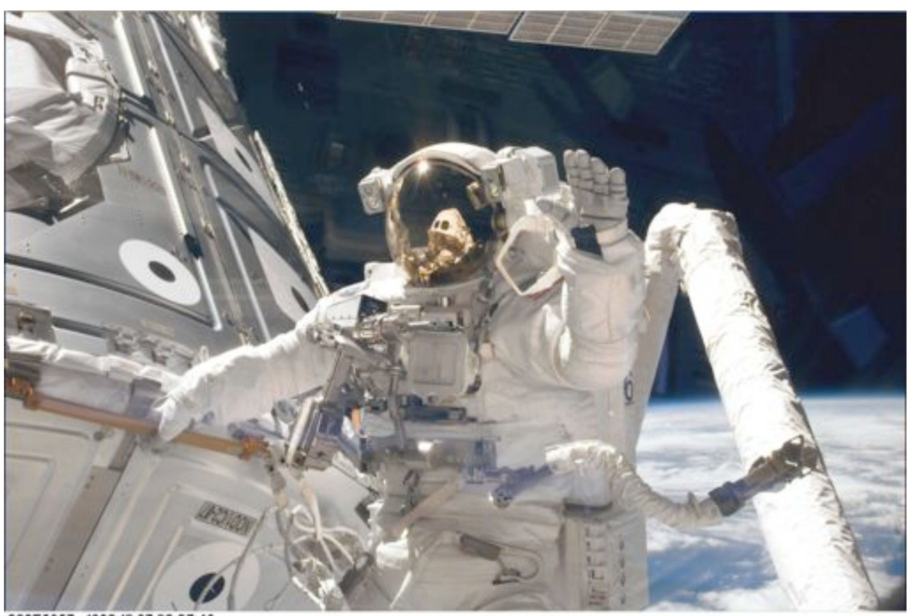


Figure 8-10. EMU, Body Restraint Tether & Pistol Grip Tool with 6 " Extension Socket

As robotic dexterity continues to improve the need for hands on EVA could evolve into local telepresence with the astronaut operating the robotic interfaces from a crew pod or in a command & control workstation in the on-site servicing depot.

8.5 IVA / Ground Operations Including Training

Current EVA operations require coordinated support from IVA and ground support personnel. Control of equipment, circuit controls, and revisions and confirmation of procedural changes will continue to be an important role for ground support. Training of EVA crew with ground support personnel is crucial to communications and success of each EVA. Training provides the EVA crew with the necessary skills to perform the EVA tasks efficiently and to understand how proper technique can avert problems. This training also allows the crew to assess hardware problems real time and contribute to a solution to the problem.

Use of computer methods for virtual simulations of EVAs can be very cost-effective and provide insight into operational scenarios prior to flight. Accurate virtual design models are therefore important to configuration control for maintenance and servicing, as well as for future modifications.

8.6 Robotic Servicing

Robotics operations may be categorized into two types of operations, gross or large arm operations and fine or small arm operations. Current Extravehicular Robotics (EVR) techniques used on shuttle servicing missions and ISS include large arms, Shuttle Remote Manipulator system (SRMS), Space Station Remote Manipulator system (SSRMS), Japanese Experiment Module Remote Manipulator system (JEMRMS) and small arms, the Canadian Special Purpose Dexterous Manipulator (SPDM), and the JEMRMS small arm. The large arms perform the crane like functions for large mass handling, capture and berthing operations and is used as a "cherry picker" for crew and equipment translation and restraint aid at the EVA worksite. Fine robotic operations on ISS are planned for sometime after 2003 and will be done by the SPDM and the JEMRMS small arm.

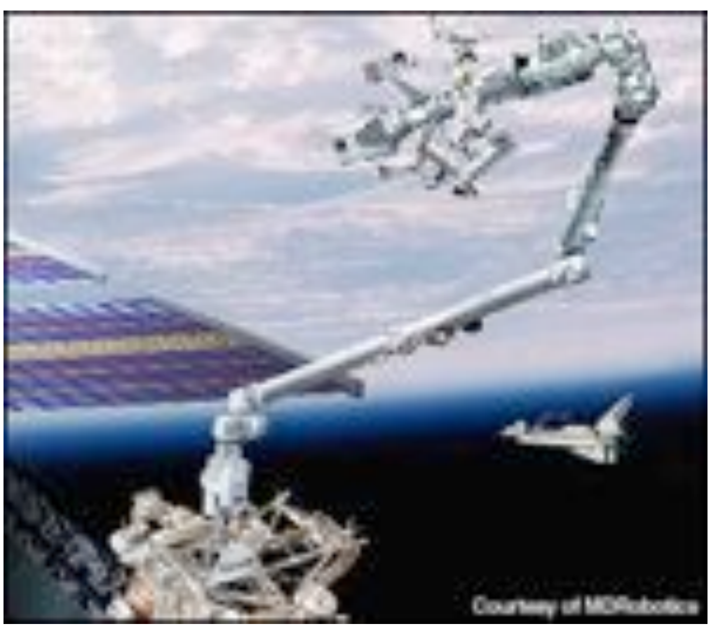


Figure 8-11. MBS, SSRMS and SPDM

Figure 8-12. IVA Work Station

Power Data Grapple Fixtures (PDGF) have been strategically located on ISS. The Space Station Remote Manipulator System (SSRMS) has the unique ability to “walk” from one PDGF to another. Combine this with the four PDGFs on the Mobile Base Servicer (MBS) mounted on the MT and the SSRMS has the ability to reach nearly all of the ISS. The MBS also has two types of robotic stowage features, the Payload ORU Accommodations (POA) and the Mobile Transporter Common Attach System (MTCAS). These features allow the SSRMS to stow equipment retrieved from the shuttle on the MBS, then translate to the worksite along the MT rail system.

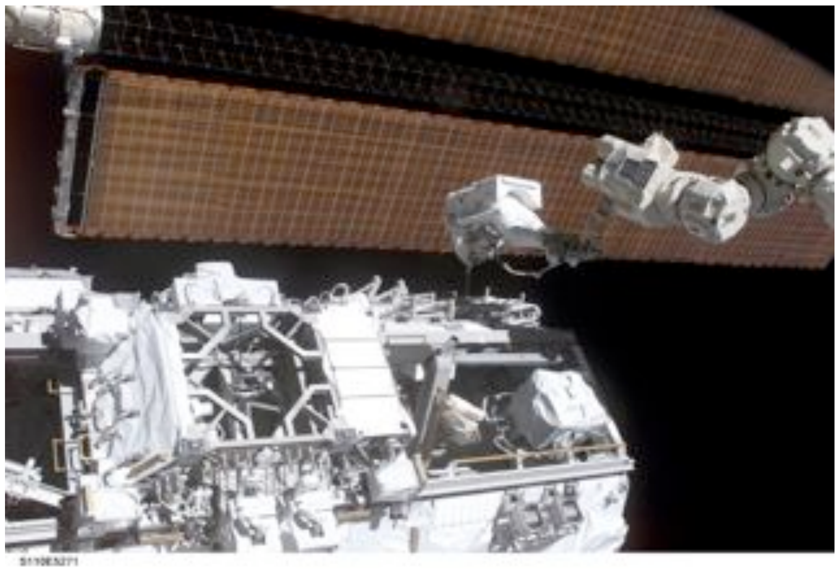


Figure 8-13. ISS Mobile Transporter on Truss Rail System

The Common Attach Systems (CAS) are located in six locations on the inboard truss of ISS. This system allows for the attachment of logistics carriers and attached scientific payloads using the SSRMS. All of these systems have applications on future large space platforms to assemble and store materials and equipment on a client. These systems could also be part of a large servicer spacecraft to transport equipment and materials to a gateway, servicing outpost or other servicing location and then conduct the assembly and servicing tasks required.

When the SPDM arrives on ISS it will perform the telerobotic remove-and-replace maintenance of designated Orbital Replaceable Units (ORUs). The SPDM attaches to the end of the SSRMS where it receives it power and data . The SSRMS translates the SPDM to a designated EVR worksite. The ISS structure provides the stabilizing H fixture for the SPDM arm used to stabilize itself. The second SPDM arm is then used to perform the ORU changeout. The SPDM provides a temporary platform for ORU stowage. The various end effector tools required for the changeout are stowed on the lower body. The ISS ORUs that can be removed and replaced by the SPDM must meet many requirements for arm access, mass handling, visual cues and alignment features. There are many ORUs on ISS that the SPDM is not capable of maintaining and require EVA for servicing. The robotic systems on future spacecraft servicers should be able to work on many different clients while imposing minimum design requirements.

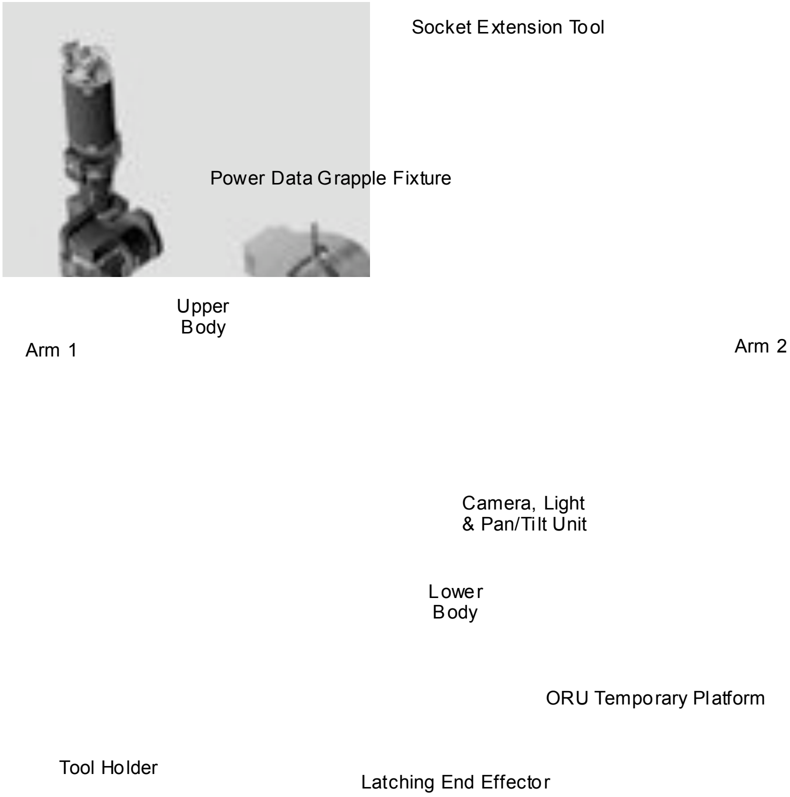


Figure 8-14. Special Purpose Dexterous Manipulator[10]

Currently all ISS EVR servicing tasks are designed to be done by EVA in case the robot fails to perform the task, but the opposite is not true for EVA tasks. The SSRMS is the first space robot to be serviced in space by EVA. Future spacecraft designs that are sensitive to EVA effects must address the contingency plans for EVR failures through EVR-to-EVR repairs.

Figure 8-15. STS111, First EVA repair of SSRMS

These arms are all teleoperated by a trained IVA crewmember on Shuttle or Station and currently can involve several crewmembers for the large berthing and assembly operations. The WSS system and targets are required to provide the visual cues needed to guide the arm operator. The capture envelopes around the EVR interfaces, grapple fixtures or H handles must be kept clear of surrounding structure or outfitting. EVR worksite analysis provides a method to verify the design meets these EVR requirements. EVR analysis is also done to check for collision paths and acceptable angles of departure from nominal during EVR berthing of large structures.

Current autonomous robotic servicing is limited to resupplying fuel to the ISS by the Progress vehicle. Autonomous SSRMS camera inspection of external areas and SPDM ORU changeout are still being developed for ISS. Additional autonomous resupply of ISS is planned with the European Automated Transfer Vehicle (ATV) and the Japanese H-II Transfer Vehicle (HTV) vehicles.

Figure 8-16. Progress Supply Vehicle

Figure 8-17. Automated Transfer Vehicle [11]

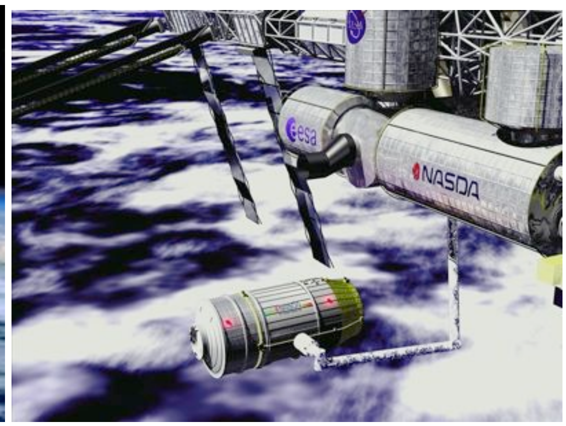


Figure 8-18. Japanese H-II Transfer Vehicle

Orbital Express is a technology demonstration system using integrated servicer and client spacecraft. The client satellite is specifically designed to provide the features required by the servicing satellite to demonstrate autonomy, rendezvous, proximity operations, standardized interfaces, refueling, and component changeout.

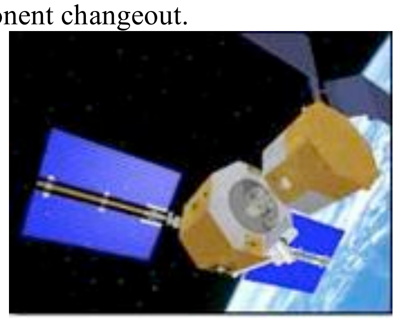


Figure 8-19. Orbital Express Demonstration System [12]

8.7 Future Designs, Approaches, and Concepts

Future autonomous servicing of space vehicles will require traveling to a rendezvous location, and servicing the client satellite. This requires having the capacity to capture, refuel, remove and replace ORUs, and release the client. The types of interfaces, berthing, docking, electrical, fluid, structural restraints must be capable of working with the servicing vehicle.

One method under development to meet this demand is the use of robotic systems, with capabilities ranging from simple teleoperation to complete autonomy. The Ranger Neutral Buoyancy Vehicle is designed to demonstrate the ability of a free flying telerobotic system to perform many required operational tasks including EVA worksite preparation, on-orbit refueling, instrumentation package replacement, and deployment of failed mechanisms such as antennae and solar arrays. By combining current robotic technology with a free-flying spacecraft bus, Ranger embodies a new class of highly capable space vehicles that will help meet the demand for future space operations. Ranger by performing many of the EVA overhead setup tasks would allow the EVA crew tasks to be optimized to take advantage of what humans do best and maximize the EVA timeline.

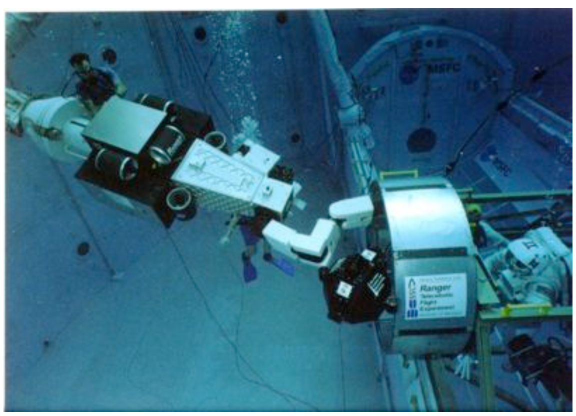


Figure 8-20. Ranger Servicing Tests [13]

Figure 8-21. Skyworker [14]

Space Worker from Carnegie Mellon University is a walking dexterous arm very suitable for repetitive structural tasks such as truss and segmented mirror construction and servicing. Space Worker is non-propulsive and requires a consistent truss cross section to grasp, and bear translational and operational loads. Space Worker would be used in teams to move and assemble materials in the assembly of large space structures and conduct the servicing after assembly is complete. Other robots could be designed to perform specific tasks allowing the design of these machines to be optimized for these specific tasks and while simplifying their design.

Robonaut is a humanoid robot designed by the Robot Systems Technology Branch at NASA's Johnson Space Center in a collaborative effort with Department of Defense Advance Research Projects Agency (DARPA). The Robonaut project seeks to develop and demonstrate a robot that can function as an EVA astronaut-equivalent. Robonaut is operated by telepresence. Astronauts are linked to Robonaut's eyes and hands using special gloves and goggles. Robonaut's actuators can then mimic the astronaut's movement. EVA tasks that were not specifically designed for robots can be performed by Robonaut, eliminating the need for special robotic interfaces. [15-16]

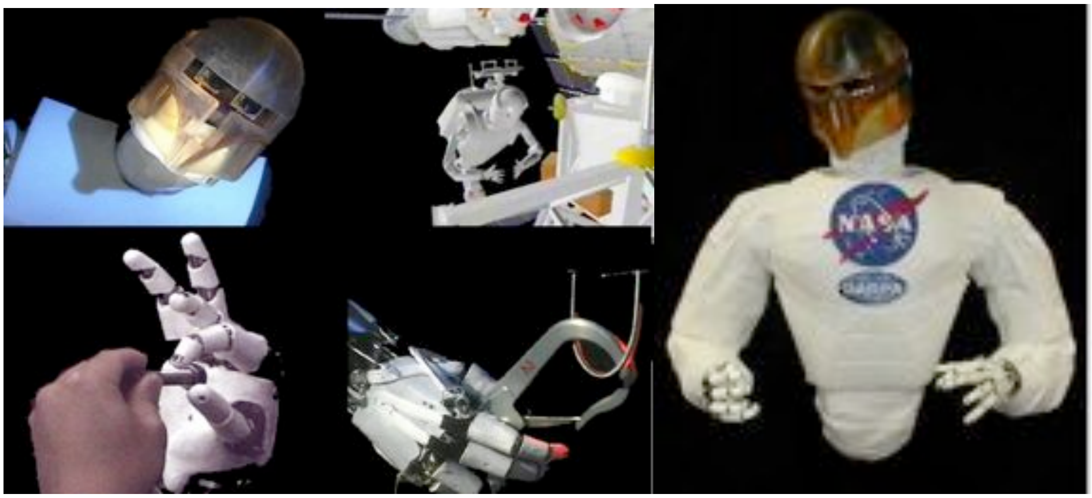


Figure 8-22. Robonaut [15, 16]

The Autonomous EVA Robotic Camera (AERCam) and Supplemental Camera and Maneuvering Platform (SCAMP) developed by Space Systems Laboratory at the University of Maryland are being developed for NASA to be an autonomous set of eyes for inspection and monitoring of EVA and EVR activities. The system will be capable of finding it's way around the ISS, inspect for damage or status of equipment. During EVR operations it can supplement the robotic arms camera's and provide ground control images of EVA activities in areas not covered by the ISS cameras. Ultimately it will be able to assess the data collected from inspections and to determine if an autonomous repair or human intervention is required. [17, 18]

Figure 8-23. AERCam on STS-87 [17]

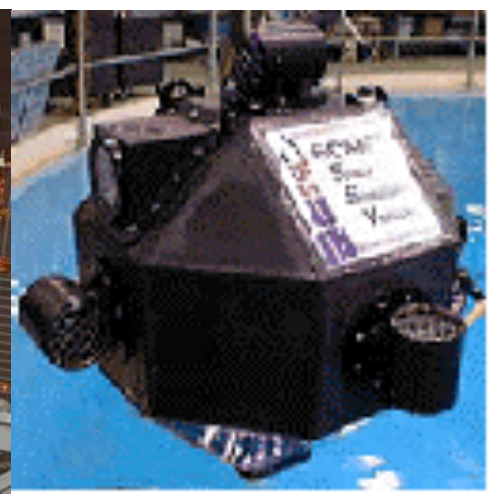


Figure 8-24. SCAMP [18]

The challenges of spaced-based assembly and servicing requires balancing EVA and EVR technologies to take advantage of the strength of each area to reduce risk and cost while still achieving mission objectives. The current state of technology for near-term servicing of satellites favors EVA methods over EVR when the client is accessible to humans. As robotic technology continues to evolve satellite servicing could become less dependent on human intervention.

9. Future Directions

9.1 Challenges and Issues

As discussed in the previous sections, the history and lessons learned from in-space servicing by EVA goes back to the early Space Shuttle program, and earlier. An experience base has been built with projects such as the Hubble Space Telescope (HST), the International Space Station (ISS), and multiple satellite rescue and retrieval missions. When the tasks to be performed in space are well-known in advance, and the serviceability is designed into the spacecraft to be serviced, then EVA servicing is reasonably straightforward: the tasks are pre-planned, stable platforms are used, and the connections and mobility aids exist and are usable. In principle, the same is true of robotic servicing if the tasks are pre-planned and designed into the system, with less restriction on the orbital location of the operations -- EVA is more flexible in terms of adapting to unplanned events, or to new conditions, but it requires a complete human infrastructure, including the vehicle that brings the crew to the operations site, life support, assured capability to return to Earth, and EVA suits. The technology of robotic processes is gradually improving, especially when the procedures are well-known, as in biotechnology laboratory analyses and manufacturing processes. Our experience with robotic assembly and servicing operations in space is far more limited than terrestrial industrial processes and the tools, interfaces, and procedures don't always exist. Robotic servicing might appear initially to be more attractive from the mission planners' perspective because it avoids the costs and restrictions associated with human operations in space. However, if the operation is to be performed in a location that is human-accessible, the added flexibility and insight of the human crew generally allows higher mission assurance with either active participation or oversight. A direct comparison between EVA and robotic solutions to specific operational problems is very difficult to make without substantially more operational experience in space than currently exists.

Planning for the future of in-space assembly and servicing requires knowledge of missions that have used these capabilities. Additionally, it requires transportation to and from the worksite, with the appropriate capability for humans and/or robots and required tools, communications, servicing equipment, etc. Infrastructure also includes the ground-based needs, for mission planning and operations. The following sections describe key technology requirements, and suggest a timeline and roadmap for developing these technologies to the level for which space-based servicing can be considered available technology.

9.2 Infrastructure

Infrastructure requirements can be divided into four general areas: transportation, servicing vehicle, flight support to the vehicle being serviced, and ground support. Transportation is a major element in the overall feasibility of in-space assembly and servicing. If the servicing is to be performed by humans, the current infrastructure limits the transportation vehicle to the Space Shuttle, in LEO orbits that don't exceed about 800 km apogee or 57 degrees inclination. NASA does not currently have plans for human transportation beyond these limits, although the Gateway Telescope assumes routine human presence in the Earth-Moon L1 region. Human operations at the Gateway requires a Crew Transfer Vehicle. As a consequence of developing the Gateway infrastructure, this would allow human access to other orbits that are not accessible by the Space Shuttle. This human presence should include a habitat equipped to provide a shirt-sleeve environment for at least a few weeks, with airlocks and high differential-pressure EVA suits to allow routine EVA operations. Any servicing to be performed at other locations will require some form of orbit transfer vehicle. If the operation is to be other than a unique mission, it is likely that an infrastructure will be developed to maintain the servicing vehicle in space, with refueling/reoutfitting capabilities. One location for this storage and maintenance port might be the International Space Station. The advantage to using ISS would be ready logistics for refueling and servicing the servicer, delivering/storing orbital replacement units for both the servicer and the vehicle to be serviced, and expendables such as air, water, and food.

Assuming that plans call for a gradual buildup and evolution of in-space servicing capabilities, with more and more frequent operations, a set of standards will be required for interfaces and tools. The requirement will be to ensure that the tools are in place to perform the operations called for in the mission design, and to ensure that the spacecraft interfaces are standardized to accommodate the tool kit. Metrics for designing the tool kit should include commonality wherever appropriate, mass and resource requirements, and flexibility to react to unplanned events.

All in-space servicing will require a standard ground support facility, with adequate remote vision and uplink/downlink command authority. For robotic servicing, the ground crew will monitor the operations as a minimum. For the foreseeable future, it is expected that the ground crew will very carefully direct the operations on a step-by-step basis, with essentially real-time control of each step. This requires adequate real-time vision with video cameras and lighting installed on the servicing vehicle at appropriate locations, with the necessary power and communications to use the cameras.

9.3 Potential Applications

The current state of the art in satellite servicing was summarized in Table 4-1. It consists primarily of capture and retrieval of satellites in Space Shuttle-accessible orbits. Some of these satellites were redeployed on the same Shuttle mission (Syncom-IV, Intelsat-VI, Solar Max) , one was returned to Earth (LDEF), and some were returned to Earth and relaunched on a separate mission (Westar, Palapa). The Hubble Space Telescope has witnessed four servicing missions. Each mission used the Space Shuttle to perform a mix of operations, some of which were scheduled servicing events, some were preplanned repair, and some were unplanned repair "workarounds". The International Space Station (ISS) is currently in the process of being assembled in space with elements from multiple Shuttle flights, as well as undergoing on-orbit repair and maintenance. The scope of potential applications of satellite assembly and servicing can be far broader than this.

With respect to satellites in low-Earth orbit, there are at least three activities currently underway. The DARPA-funded Orbital Express program will demonstrate fuel transfer and ORU replacement on a satellite designed for this operation, by a compatible servicing satellite. This demonstration is scheduled for 2005. HST and ISS are serviced on a planned schedule with appropriate accommodations.[4]

In the near-term, satellite servicing in Shuttle-accessible orbits can evolve to address both pre-planned and unplanned robotic operations. This can be expected to include satellite refueling, replacement of ORUs, upgrades of equipment and instruments, and simple repair operations, using both EVA and robotic systems. The robotic operations can be further developed through a program of ground-based demonstrations, followed by flight validation. Once flight demonstrations have been accomplished, it seems reasonable that this technology should apply to all low Earth orbits, including high-inclination and elliptical orbits. As the technology matures, it should see a gradual evolution to more complex operations, potentially including major repairs.

Robotic servicing will expand the range of orbits to all low Earth orbits, and higher. Higher Earth orbits, such as geostationary orbits, are likely to be served by robotic servicing vehicles rather than astronauts for the foreseeable future. Most of the same operations that are to be demonstrated in LEO will apply in GEO: robotic refueling, ORU replacement, upgrades, and simple repair. Geostationary satellite servicing will be aided by the presence of in-space servicing vehicles that remain either in GEO or at the ISS. This technology would be greatly aided, and possibly supported by commercial partners, through demonstration of repair and return to service of commercial and government-owned satellites. A potential application might be to repair or replace large-scale components, such as an antenna, solar panel, or thermal blankets. This could then be a precursor to an ongoing commercial enterprise.

Space-based assembly of large structures should also continue to be developed, as it is being developed for ISS. This has already begun with simple joining of two or more payloads in space that were designed from the outset to be integrated into a single facility. A candidate mission is assembly of large space telescopes, which could evolve into assembly and maintenance of solar power satellites, large military satellites, or interplanetary spacecraft which are too large to be launched as a single payload. This last category would also include integration of vehicles for human exploration beyond Earth orbit.

A Gateway architecture would be further out in time. This would involve a permanent, human-tended outpost at Earth-Moon L1, with supporting infrastructure. Standard tool kits and versatile robotic servicers would facilitate the development and use of a multipurpose Gateway site. Transportation systems and a logistics depot are also required. Early studies of technologies, benefits, and risks could shape the direction of the Gateway.

9.4 Technology Requirements

As stated in the previous sections, the technologies to be developed for a robust human and robotic servicing capability in space are generally a balance between standard interfaces for well-planned operations and increasing autonomy for astronauts and robots. There is also the separate issue of transportation and storage on orbit of fuel, vehicles, tools, and ORUs. The ISS currently uses the Multipurpose Pressurized Logistics Modules for transportation of cargo. The technologies should be developed through a series of prototype applications and testbeds. Starting with the subject of standard interfaces, both the servicer and the client vehicle should have standard, well-known interfaces for ease of operations. These interfaces should include the physical interfaces, such as connectors, bolts, and release mechanisms, as well as software interfaces for compatible uplink commands. The interfaces should be compatible with the end effectors such as the special purpose dexterous manipulator.

In parallel, development of handling and manipulation tools, and general-purpose dexterity in astronautics and telerobotics, can provide servicing capabilities for medium-complexity tasks, enabling servicing missions for spacecraft which have not incorporated a full suite of serviceability features.

The robotics technologies will evolve through a series of applications, in parallel with the gradual evolution of the robotics industry in general. Beginning with accomplishing simple tasks with well-planned operations, such as observed today in such diverse industries as pharmaceuticals and automobile assembly, this will evolve to perform operations with uncertain interfaces with knowledge capture and learning, leading eventually to the ability to perform complex tasks with complete autonomy.

Toolkits will be required for a range of tasks, for connection and disconnection, for exerting force, for cutting and joining, for circuit testing, for fluid transfer, and for placement of equipment for storage or temporary hold-down. The toolkits will also include mounting platforms for the astronauts, the robotic servicers, and the serviced vehicle. Storage containers and environmental controls will also be needed.

Extravehicular technologies require improvements in gloves, spacesuits, and communications. Current programs are working to improve glove flexibility to allow more dexterous operations. Improvements in suit design will allow a greater range of movement, allowing for more EVA capability. Suit improvements also should allow a greater range of astronaut physical sizes and mobility, and reduce pre-EVA preparation time. Video from other crew and a heads-up display on the helmet is planned to facilitate communications with other astronauts and with the ground, as well as higher quality vision.

While evolution of the servicing vehicle capabilities will continue, it is possible that greater progress can be made with higher leverage simply by designing serviceability into the satellite from the outset. This is indigenous to the design and demonstration of the NEXTSat client satellite for Orbital Express. The satellite can be designed for ease of servicing through careful consideration of standard interfaces, accessibility, and factors such as avoiding permanent bonding adhesives, welding, and such connections as Lok-Tite, etc. Serviceability is also enhanced through preparation of mounting ports, berthing adaptors, and handhold fixtures.

However, as general-purpose telerobotic capabilities evolve in development, the ability to service spacecraft which are not specifically designed for servicing will become more productive and more reliable, decreasing the dependence on human access for medium-complexity servicing interventions, albeit at a higher level of mission risk than designed-for-servicing cases.

Space-based assembly will be more involved. The early technologies of remote docking and berthing, and EVA assembly of large structures, have already been demonstrated through programs such as ISS and Shuttle deployment demonstrations; e.g. the solar array unfolding experiment, but complex assembly operations are still in the planning stage. Assembly will require many of the same technologies as servicing, including standard interfaces and toolkits, mounting sites, cameras, and orbital storage sites. One advantage of space-based assembly over satellite repair is that the spacecraft is designed from the outset for the operations being planned.

Two additional technology steps that are required for in-space servicing involve transportation and storage on orbit. If the operation is to be performed with the Space Shuttle or at the ISS, then these items will not involve new technologies, but may require development of additional servicing capabilities at ISS or with STS. If any other location is used, for assembly/servicing operations or if the spacecraft will transfer to a different orbit after the operation is complete, then an orbital transfer vehicle will be required. For missions that will not return, such as planetary missions, this might simply be an upper stage. For missions to different orbits or to establish a capability for servicing a series of accessible client spacecraft, a space-based OTV will be required. This OTV might then require a depot for storage and refueling. The depot could also be a storage site for tools, spare parts, assembly elements, and ORUs for the serviced satellite. Alternatively, if the OTV incorporates built-in interfaces, navigation, rendezvous, and servicing capabilities, it could rendezvous in high orbit with a compatible ELV-launched package and service itself using the package as a temporary once-only depot.

9.5 Technology Roadmap

Figure 9-1 shows one plausible roadmap to develop the technologies described above. There are a number of ground-based testbeds in operation today, at University of Maryland, Carnegie Mellon University, and at NASA Langley Research Center and Johnson Space Center. These should be developed to demonstrate the complete range of operations for satellite refueling, service, repair, and maintenance. By exploring the full range of operations, we will learn valuable lessons that will support the objectives of flight demonstrations and trade studies of optimizing the servicing techniques.

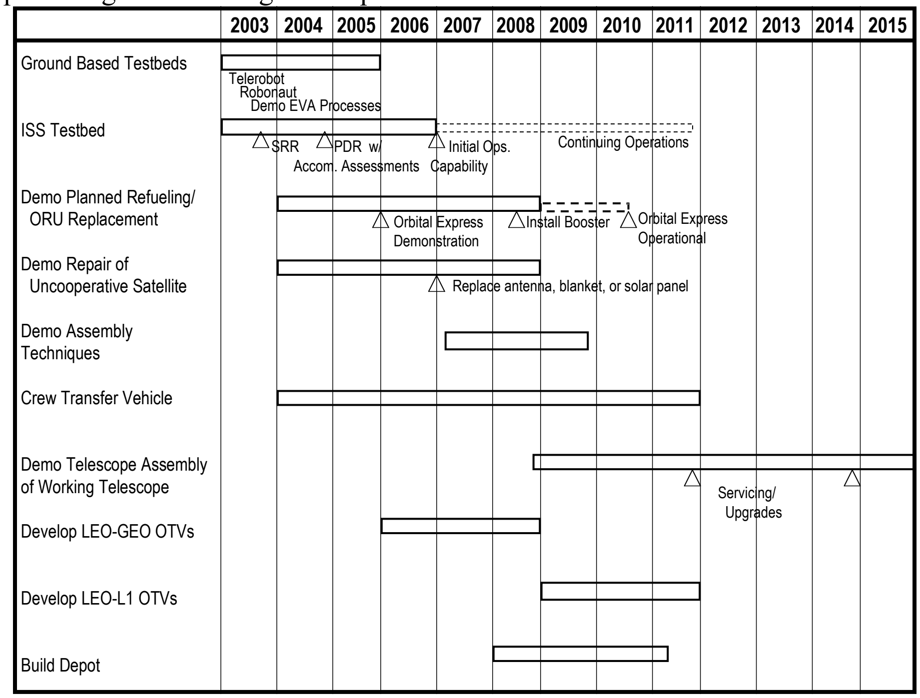


Figure 9-1. Technology Roadmap

Ground-based testbeds provide a platform to affordably develop the software and the processes for most of the tasks that will be performed in satellite servicing, but the technology and the processes will still need to be validated in the space environment. The actual operating environment will involve microgravity, vacuum, and thermal extremes, while posing the logistics challenge of ensuring access to all the needed tools, hold-down platforms, and reactive forces on the satellite being serviced. To truly validate the processes, and to instill confidence leading to acceptance of the technologies for actual systems, space-based demonstrations will be required. The ISS provides an ideal platform for a multi-purpose servicing testbed – it has attach points for the client satellite and for tools; it has onboard astronauts to conduct EVA operations; it has the required communications, power, and data management utilities; and it has routine logistics to transport equipment and fluids up and down. Assuming a five-year timeline to achieve initial operational capability on-orbit suggests an early start on the design process, with a thorough system requirement development phase as soon as possible. Following definition of the system requirements will be a preliminary design phase for the testbed as an operational system, and as an ISS payload with accommodations requirements and demands. It is expected that, even after initial operations, the testbed will evolve as we gain experience and better definition of functional systems to be developed with these technologies.

Demonstration of satellite servicing technologies should proceed in at least three phases: ORU replacement of a satellite designed for the operation, fluid transfer to such a cooperative satellite, and repair of a satellite that was not specifically designed for this mission. The Orbital Express program plans to design, build, and flight demonstrate a pair of satellites to accomplish these first two demonstrations by 2005: a servicer and a target satellite will enter orbit and conduct a series of operations to include ORU replacement and refueling. If satellite servicing is to be considered a mature technology, then a follow-on demonstration should attach a booster to lift a servicer satellite into a higher orbit.

Another flight test should be undertaken to demonstrate the ability to repair a satellite that was not initially designed for repair, i.e. does not have specific attach points and/or pre-planned release mechanisms. Such a demonstration would include replacement of a major system or removal/replacement of particular instruments. A plausible early step would be replacement of antennas, thermal blankets, or a solar panel, as discussed earlier. Based on the current state of the technologies, this can be conducted within about five years. Development and test of telerobotic handling and manipulation, with visual and other forms of interactive feedback, are needed and may be provided in near-term plans if adequately funded. Mission support features for data, communications, power, attitude control, relative navigation, generic structure grappling, temporary stowage and environmental protection, staging of tools, materials, and replacement parts are needed for a full mission development, integration, and execution.

Assembly of large structures, such as telescopes or solar power satellites, will be somewhat more complex. This technology has been greatly advanced through ISS assembly, a process which continues today. The development of near-term technology for repair of satellites not designed for repair will constitute another significant advance of the technology needed for in-space assembly of complex objects. The next step might be to demonstrate assembly of a simple structure, either telerobotically or with EVA. The ISS might be used as a base for a series of demonstrations of assembly techniques. The following step would be assembly of an actual telescope in space, either at or near the ISS, or at the Earth-Moon L1 Lagrange point. For a technology development plan, this is assumed to be about a decade in the future.

Except for those demonstrations that are in LEO, especially in Shuttle-accessible orbits, there will also be a need for orbit transfer vehicles and crew transfer vehicles. It is assumed that these will be driven by a combination of chemical and electric propulsion from a parking orbit in LEO to perform the operations – either in GEO or L1 – and then return to the parking orbit to await another mission.

As the technology matures, both for in-space assembly and servicing and for the orbit transfer vehicles, the demand for such services will grow. As the demand grows, there will be a time when it is cost-effective to build a long-lived depot in space to park the servicer vehicles and to store tools, fuels, and ORUs. This depot might be at the ISS, or another location might be more attractive.

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